Observation of Resonance in Beat-Wave Experiments with Nd Lasers

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Abstract
We present experimental results obtained in a beat-wave experiment performed with both Nd-YAG (1.064 mm) and Nd-YLF (1.053 mm) laser wavelengths in a D2 plasma. The two infrared beams together with a green probe beam are focused colinearly in a gas chamber filled with D2 at different pressures. The green light scattered by the plasma is observed at 0°,10° and 30° from the incident direction. The 10° data clearly show the presence of a resonance when the plasma frequency is close to the frequency difference between the two pump beams.

The need for new particle acceleration techniques has led us to investigate the possibility of using plasmas to convert the transverse electric field of a high power laser into a high amplitude high phase-velocity electrostatic field. Plasmas can sustain electric fields many orders of magnitude higher than available in conventional accelerating structures[1]. A relativistic electron plasma wave is excited by two copropagating intense laser beams with slightly different frequencies. This is a resonant process in which the natural oscillation frequency of the electrons ω_p has to be close to the frequency difference $\delta\omega$ between the two beams. The wave amplitude grows in time until it saturates because of several different mechanisms[2,3]. A relativistic plasma wave has been observed in CO_2 ($\lambda \approx 10\mu m$) laser beat-wave experiments[4,8] and its saturation attributed to relativistic detuning[7] or mode coupling with the ion waves generated by stimulated Brillouin scattering[5]. Indications of a beat wave were reported with Nd ($\lambda \approx 1\mu m$) lasers[9]. In our experiments, we produce electron plasma waves by a beat-wave using also two 1µm laser beams. The electron waves then decay by modulational instability[3] (M.I.) into ion waves and electron waves of lower phase velocities, which we then detect. M.I. is a four wave coupling : a high amplitude electron plasma wave decays into ion density perturbations and two daughter electron waves. The maximum coupling is obtained for daughter waves along the plasma wave electric field, but taking into account a possible finite aperture for the original plasma waves, we can expect daughter waves in all directions.

The experimental set-up is shown in fig 1. The two pulses delivered by a Nd-YAG and a Nd-YLF oscillator are amplified in the laser chain of the LULI up to 7J with an output diameter of 90mm. The YAG (YLF) pulse at 1.064 µm (1.053 µm) wavelength is 160±10ps (90±10ps) wide (FWHM). A 30mm diameter KDP frequency-doubling crystal set-up in the middle of the main beam generates a 300mJ green ($\lambda = 5320$ Å) probe beam. A 1m focal length bichromatic doublet focusses these beams in the middle of the gas chamber filled with deuterium. A 30mm diameter block is put at the center of the YLF beam in order to avoid any wave coupling and satellite generation in the optical elements traversed by the three beams of different wavelengths[10]. The focal spots are imaged with a high magnification on a CCD camera giving respectively diameters of 100±20µm (FWHM) and 40±10µm for the infrared and green beams. The maximum intensity of the pump beams is $3.2\ 10^{14}$W/cm^2 (YAG) and 6.10^{14}W/cm^2 (YLF). The pressure and temperature of the gas are adjusted with an accuracy that allows a precision on the initial atomic density better than 0.3%. Preceeding experiments[11-13] have shown that near the focus of the lens the gas is fully ionized by multiphotonionization so that the initial electron density is equal to the atomic density. The probe beam light scattered in the plasma is imaged with a magnification of 1 at the entrance of two spectrograph-streak camera combinations at 2 different angles : 0° (f/30 optics) and 10° (f/10) or 10° and 30° (f/10). The gas chamber and the alignment system are described in detail in ref 12.

The relativistic plasma wave generated by the beat-wave can only be detected on the 0° channel. The modulational instability then generates a broad spectrum of waves. The 10° and 30° channels are used to detect instability waves propagating at nearly 90° with respect to the laser axis. From the measured electron temperature[13] $\approx$15 eV and density $\approx 10^{17}$cm^{-3}, a Debye length λ_D of 0.1 µm. is inferred.

A typical time-resolved spectrum obtained on the 10° channel near the resonant density is shown in fig 2. The central unshifted line is attributed to ion waves with very low frequencies. On each side of this central line appear two or three satellites with frequency shifts equal to $\delta\omega$, $2\delta\omega$ and $3\delta\omega$. Fig 3 a,b,c exhibit respectively the behavior of the central unshifted line, of the first and second plasma satellites as a function of the D_2 gas filling pressure. It clearly shows the resonant behavior of the electron and ion waves near the theoretical resonant pressure (1.65 Torr at 23°C) : a rapid increase of the signal on the low density side and a slower decrease on the high density side. *All these lines disappear when we use only one laser frequency or when the initial pressure is too low.*

By comparison with the thermal scattering level which can be calculated from the temperature and density[14], we can estimate a minimum scattered intensity measured at 10° for the electron waves at $\delta\omega$ and the ion waves of respectively $I_s/I_0 \geq 5.10^{-9}$–5.10^{-8} and $I_s/I_0 \geq 6.10^{-8}$–6.10^{-7}. The classical Bragg formula relates the scattered intensity I_s to the probe beam intensity I_0 :

$$\frac{I_s}{I_0} = \left[\frac{\pi}{2} \frac{\delta n}{n_0} \frac{n_0}{n_c} \frac{L}{\lambda} \right]^2$$

where $\delta n/n_0$ is the relative amplitude of the density perturbation, n_c is the critical density associated with the probe beam wavelength λ, L is the length of the plasma in the direction of observation. For a probe beam diameter of 40 µm it gives L = 230 µm and the corresponding relative density perturbations $(\delta n/n_0)_{10°} \geq (0.4$–$1.2)\%$ for the electrons and $(\delta n/n_0)_{10°} \geq (1.2$–$3.7)\%$ for the ions.

With some reasonable hypotheses, we were able to estimate a lower limit of the beat-wave generated density perturbation of 1% to 5%. We emphasize that this gives a local estimate of the value of the electric field independant of the assumptions made on the actual volume filled by the plasma waves.

At 0° the signal at the frequency of the probe beam is blocked in the spectrometer so that the electron satellites at $\pm\delta\omega$ are detected and the ion feature is suppressed. The intensity of the first satellite as a function of pressure does not show a clear resonance. However, an important point is that we do observe some satellites even at pressures below the resonant pressure. Null shots in vacuum do not produce these satellites meaning that the signal is generated in the neutral gas surrounding the plasma. The third order nonlinear susceptibility $\chi^{(3)}$ of the gas couples together the two laser beams and the probe beam[15]. A signal is therefore generated in the volume of gas common to the three beams and, having the same frequency, can hide the signal from the plasma wave. For the points near the resonance we get an upper bound of the intensity scattered by the relativistic plasma wave of the order of 10^{-5}–10^{-7}. This gives an upper bound of $(\delta n/n_0)L$, the product of the amplitude of the plasma wave by its length of (0.4 – 4)% mm. This assumes moreover that the plasma wave is coherent over the whole scattering length. We must emphasize that the absence of observed resonance at 0° is mainly due to an experimental problem with the diagnostic and is not in contradiction with the 10° results.

The signals observed at 30° correspond to a classical thermal Thomson scattering. This shows that because of Landau damping no electron waves or ion waves are generated with the corresponding k vector.

A coherent interpretation of all these results is the following. In a first step relativistic plasma waves are generated by the beating of the two infrared lasers beams. As their amplitude increases these waves become unstable with respect to M.I. A whole spectrum of waves is then amplified from the thermal noise and we measure those propagating at 95° on the 10° diagnostic. An estimate has been made of the saturation level of the relativistic plasma wave due to M.I. Assuming a homogeneous initial density we calculate with the use of usual fluid equations the growth of the relativistic plasma wave. At each time step we compute the growth rate of the M.I and assume that the wave saturates when the time integral of the growth rate reaches a value of 5 as suggested by particle simulations[3]. At this value for our experimental conditions the saturation value of $\delta n/n_0$=1.5% is reached about 50 ps before the maximum of the laser pulses. For comparison ,we note that in the absence of M.I, the saturation due to relativistic detuning[2] would lead to a maximum value of 14% near the maximum of the pulses.

We also have some evidence that the ponderomotive force of the laser itself modifies the density profile of the plasma leading to local depletions of the initially homogeneous density[12,13]. This explains the assymmetric feature of the resonance curve : for an initial gas pressure below the resonance pressure, the plasma never reaches the optimum density ; on the opposite if the plasma is initially overdense it may go through the right value during the laser pulse, and this effect is observed even for very high initial pressures 2 to 3 times higher than the resonant value.

In conclusion intense ion and electron waves due to the decomposition, of beat-wave generated electron plasma waves near the resonant density via modulational instability have been observed Although the amplitude of the relativistic plasma wave has not been measured directly, we can estimate it from the amplitude ratio between satellites observed at 10°. This estimate of the density perturbation (≈ 1-5%) is in agreement with simple predictions of the maximum amplitude of the plasma waves generated by a beat-wave in the presence of modulational instability .

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FIGURE CAPTIONS

Fig 1 : Experimental set-up. The three wavelengths (YAG, YLF and doubled YAG) are spatially distributed as shown and focussed in the middle of the gas chamber.

Fig 2 : A scattered spectrum measured at 10° in D_2 ,1.95 Torr, $I_{max}(YAG) = I_{max}(YLF) = 10^{14} W/cm^2$. The central line ($\omega_{probe}$) is attenuated by 100 and the first satellites ($\omega_{pr} \pm \delta\omega$) by 10. Lineouts at the maximum of the emission are shown on the right

Fig 3 : Intensity at 10° as function of normalised fill pressure p/p_{res}. p_{res} is the theoretical resonance pressure (1.65 Torr). (a) : central line (ω_{pr}) ; (b) : first satellite ($\omega_{pr} + \delta\omega$); (c) : second satellite($\omega_{pr} + 2\delta\omega$). The three vertical scales use the same unit. The points on the x axis are respectively 5, 4 and 2 orders of magnitude lower than the maximum signal

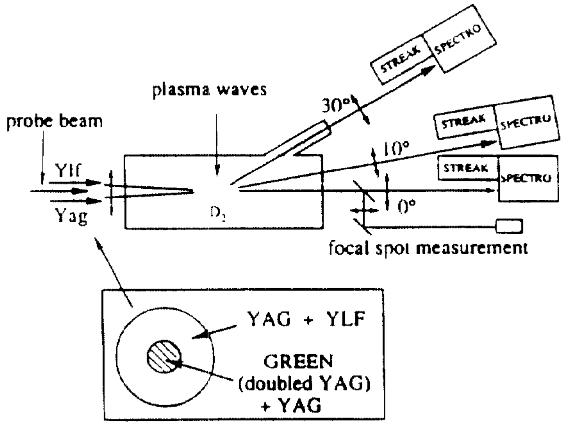

Figure 1

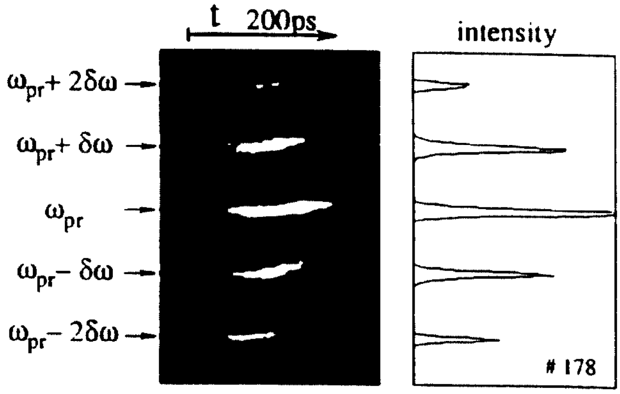

Figure 2

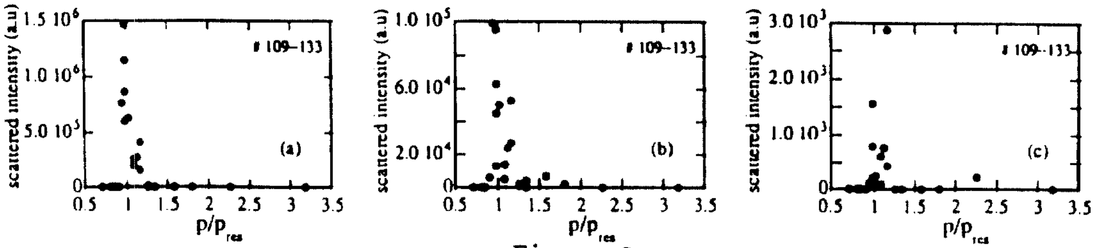

Figure 3