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OBSERVATION OF PLASMA ION OSCILLATIONS IN A LASER-PRODUCED PLASMA*

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(Received 14 April 1967)

Experiments with 6943-Å light scattered from a high-density carbon plasma have resulted in the spectroscopic observation of ion wings produced by plasma ion oscillations. For an energy density of 200 J/cm^2 and a pulse half-width of 90 nsec, the maximum separation of the ion wings was found to be 0.9 Å. This corresponds to a plasma electron temperature of more than 25 eV and a density of 10^{19} electrons/cm^3.

Since the invention of very intense, monochromatic light sources in the form of lasers, the scattering of light from plasmas has received much attention because of its potential as a plasma diagnostic tool. It is, for instance, possible to obtain most of the important plasma parameters, such as the electron temperature (T_e), ion temperature (T_i), and electron density (n_e) from the spectral intensity distribution of the scattered light.

Consideration of the electron and ion density fluctuations in a plasma has shown that the resulting spectrum of the scattered light consists of a superpositioning of two spectra.[1-3] One of these is due to the high-frequency plasma electron oscillations and is characterized by a satellite peak on either side of ω_0, where ω_0 is the frequency of the incident light. The other spectral component is due to the lower frequency plasma ion oscillations and should manifest itself by splitting the ω_0 line into two symmetric components (ion wings) separated from each other by ~1 Å for a laser-produced high-density plasma. In recent months a number of authors have reported the observation of the spectrum caused by the plasma electron oscillations.[4-6] Depending on the electron density, these broadened satellite lines are generally found around 6900 and 6980 Å if a ruby laser is used. However, because of insufficient resolution, too much stray light, or a too low plasma density, the splitting of the 6943-Å line due to plasma ion oscillations has so far evaded detection.

Recent experiments conducted in this laboratory with light scattered from a ruby-laser-produced plasma have now resulted in the observation and measurement of the spectrum produced by the plasma ion oscillations.

The plasma was created by focusing the beam of a high-power oscillator-amplifier, ruby-laser system onto the flat end of a $\frac{1}{8}$-in.-diam rod of pyrolitic graphite. The Q-switched oscillator was triggered with a rotating dielectric reflector and gave an output of about 2 J with a pulse width of 90 nsec. The gain through the amplifier ruby was about fourfold.

The target was mounted on a stand inside a vacuum chamber. All experiments were conducted at a pressure of 10^{-5} Torr. A positive lens of 10-cm focal length placed before the target made it possible to select the desired energy density which was to be deposited onto the target's surface. A second lens was mounted such that its optic axis was perpendicular to both the incident laser beam and its E field (the beam was horizontally polarized). This lens collimated the scattered light coming from a small volume located at its focal point. The collimated beam was then focused onto the slit of a modified 1-m Czerny-Turner spectrometer. The reflection grating, blazed for 7000 Å with 1180 grooves/mm, had a dispersion of 8.2 Å/mm in the first order. By focusing the spectrum with a short-focal-length lens onto a film plate located 1 m from the usual focal plane of the spectrometer, a dispersion of 1.2 Å/mm was obtained with a resolution of 0.1 Å. The spectrum was photographed with Polaroid-Type 413 infrared film.

If stray light is kept from entering the spectrometer and plasma conditions are right, the spectral line of the scattered laser light should be seen to split into two lines. Scattering theory shows that because of the plasma ion oscillations, the two spectral lines (or ion peaks) will now be located at $\omega_0 \pm \omega_i$, where

$$\omega_i = \omega_p{}^2/(1+\alpha)^2. \tag{1}$$

ω_p is the ion plasma frequency and the parameter α is

$$\alpha = \lambda/4\pi D \sin\tfrac{1}{2}\theta, \tag{2}$$

where D is the Debye length, λ is the wavelength of the incident light, and θ is the scattering angle.

For the plasma studied in this laboratory it is estimated that $\alpha \simeq 7$. This is based on an interferometrically measured electron density of 10^{19} and an electron temperature of 25 eV.[7,8] Since $\alpha \gg 1$, Eq. (1) can be approximated by

$$\omega_i = (4\pi/\lambda)\sin\tfrac{1}{2}\theta(n_i kT_e/n_e m_i)^{1/2}.$$

Spectroscopic observations of the plasma indicate that $n_i/n_e = \frac{1}{2}$. Thus, based on the above equation and plasma parameters the separation of the two ion peaks should be 0.65 Å.

The maximum separation of the ion wings which we have observed so far is 0.9 Å. This occurred when the focal point of the detector lens was located in the center of the plasma at about 1 mm from the target's surface. The energy density of the laser beam was 200 J/cm^2 at the target. The larger than expected separation of the ion peaks is perhaps due to a higher electron temperature.

In one experiment the entire plasma shape was focused onto the slit, thus giving spatial resolution. The resulting spectrum showed again a splitting of the 6943-Å line with a maximum separation of 0.9 Å at the location corresponding to the hot core of the plasma. Both ion wings then gradually merged until they could not be resolved at both ends of the line corresponding to the cooler outer layer of the plasma. From these data we have calculated the electron temperature in the plasma as a function of r/r_0, where r_0 is the radius of a cross section of the plasma plume at 1 mm from the surface of the target. It was found that the plasma's temperature is constant throughout most of its diameter. The diameter depends of course on the diameter of the focused laser beam. In previous work[9] we have found that the density exhibits this same uniformity across the plasma volume.

A densitometer trace of the ion wings is shown in Fig. 1. Even though the half-width of the laser pulse is 90 nsec, the image on the photograph corresponds to an exposure of about 50 to 60 nsec because the energy contained in the first 70 nsec of the pulse is used to heat the surface of the target to its sublimation temperature. Another 70 nsec elapse until the leading edge of the plasma has traveled 1 mm away from the surface to the location of the "detector" lens, and in the remaining 50 to 60 nsec when scattering takes place it must be assumed that the pertinent plasma parameters undergo some change. Thus, when judging the trace in Fig. 1 it must be remembered that it represents a time-integrated spectrum. The effect of this is a broadening of both wings. It is for this reason we will in the future attempt to time resolve the scattered spectrum.

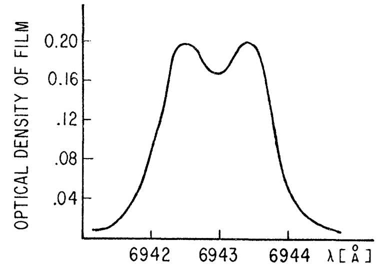

FIG. 1. Intensity distribution of scattered light as a function of wavelength.

*This work has been supported in part by the Advanced Research Projects Agency.

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OBSERVATION OF AN EMISSION PEAK AT PLASMA CUTOFF*

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The theory[1] for extraordinary wave propagation ($\vec{k} \perp \vec{B}; \vec{E} \perp \vec{B}$) in a cold plasma with $\omega_p/\omega < 1$ predicts an upper hybrid resonance frequency and a plasma cutoff frequency which are expressed by the relations

$$(\omega_c/\omega)^2 = 1-(\omega_p/\omega)^2 \quad (1)$$

and

$$\omega_c/\omega = 1-(\omega_p/\omega)^2, \quad (2)$$

respectively. $\omega_c(=eB/m)$ is the electron cyclotron frequency and $\omega_p[=(ne^2/m\epsilon_0)^{1/2}]$ is the electron plasma frequency. From a homogeneous warm plasma, one might expect to observe a radiation peak at the upper hybrid frequency. However, in a real plasma in a uniform magnetic field, in which the electron density decreases to zero at the boundary, there is a region of plasma cutoff between the hybrid resonance region and the boundary. The resulting evanescent layer causes the resonance to be inaccessible to observation from the outside.[2] Kuckes and Wong[3] predict that the emission from a plasma of this type should be concentrated about two peaks, the first at $\omega_c = \omega$, and the second at the cutoff frequency appropriate to the maximum electron density in the plasma, i.e., at $\omega_p = \omega_{p\,\max}$. They observed a peak at $\omega_c = \omega$ but did not observe a second peak. In the present experiment, we have observed two peaks in the emission from a low-pressure helium or neon discharge, which simulates a plasma slab in a uniform magnetic field.[4] We have established with good accuracy that the second peak indeed corresponds to the plasma cutoff frequency.

The experimental procedure was dictated by two principal requirements. The first was for a plasma with a variable but accurately reproducible electron density. This was accomplished by operating in the afterglow of a plasma created by an intense 21.7-MHz excitation pulse approximately 2 msec long. By changing the time in the afterglow at which the measurement was performed, the electron density was allowed to vary without changing any of the other conditions in the plasma. The second requirement was that in order to radiate above background levels, the electrons must be at a high temperature. This was accomplished by applying a short rf pulse (approximately 20 μsec long) of sufficient intensity to heat the electrons, just prior to the time of measurement. The emission was sampled by an X-band horn at a time about 10 μsec after the end of the heating pulse so as to allow sufficient time for the electron distribution to become Maxwellian. At the same time, the electron density was measured by an interferometer. The emitted power was detected by a single-sideband superheterodyne receiver having a noise figure of less than 5 dB.

Figure 1 shows the relative extraordinary-wave emitted power at 9.15 GHz for different times in the afterglow of a helium plasma. The curves were obtained from calibrated recordings which were replotted to provide a linear dB scale. These curves clearly show the presence of two peaks. Ordinary-wave ($\vec{k} \perp \vec{B}; \vec{E} \parallel \vec{B}$) emission showed only the peak near $\omega_c = \omega$ ($B = B_c$). The plasma cutoff peak is designated by an asterisk. For sufficiently low electron density (large τ), the peaks merge. With increasing density, their separation increases, the cutoff peak broadens and eventually