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Observation of Plasma-Density Modulations Produced by Ruby-Laser Light Mixing

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The effect of mixing two high-power ruby-laser beams in a plasma has been investigated by means of light scattering. Coherently scattered light has been observed with intensities of up to 30 times that scattered by incoherent thermal fluctuations. As indicated by the wave-vector distribution, the nonlinear electromotive forces of the mixed electromagnetic waves produce a stationary electron-density wave in the plasma.

Large perturbations in plasma density fluctuations may be caused by the nonlinear forces of two intense electromagnetic waves acting on plasma electrons.[1] Since the scattering form factor $S(\vec{k}, \omega) \propto \langle |n(\vec{k}, \omega)|^2\rangle$, the light-scattering properties of the plasma will be changed. In plasma atmospheres in front of solid targets where incident and specularly reflected waves mix, this effect may strongly influence the backscattering of laser light and thus may be of importance in laser-fusion experiments. It has been shown previously that two laser beams of different frequencies, when mixed in a plasma, can enhance the density-fluctuation intensity if the difference frequency coincides with the plasma resonance frequency.[2] A similar effect may be expected if the difference frequency coincides with the ion resonance. In this Letter we would like to show that even for zero frequency difference of the mixed laser beams a strong modification of the density fluctuations takes place, the nonlinear electromotive forces setting up a stationary density wave.

It can be shown[1,3] that two plane monochromatic electromagnetic waves of the same frequency induce coherent fluctuations in a plasma of the form

$$\langle |n(\vec{k})|^2\rangle = V n_0^2 \beta^2 \frac{1+Z\alpha^2}{1+\alpha^2(1+Z)}\, \delta(\vec{k}_0 - \vec{k}). \qquad (1)$$

Here

$$\beta = \frac{e^2 \vec{E}_1 \cdot \vec{E}_2}{2m\omega^2 KT}, \quad \alpha^2 = \frac{n_0 e^2}{\epsilon_0 KT k_0^2}, \quad \vec{k}_0 = \pm(\vec{k}_1 - \vec{k}_2),$$

$\vec{k}_{1,2}$ are the wave vectors, ω the frequency, $\vec{E}_{1,2}$ the electric field amplitudes of the mixed waves, and V the mixing volume. (The functions F_e and F_i in Ref. 1 are equal to unity for $\omega \to 0$.)

In the present experiment two ruby-laser beams of equal power (up to 250 MW within a spectral linewidth of 0.03 Å) are mixed in a plasma in opposite directions. The beams are focused to a volume of 0.3 mm diam inside the plasma. A third beam of frequency-doubled ruby-laser light of about 4 MW is used for light-scattering diagnostics, being focused into the focal volume at an angle of 60° with respect to one mixing beam and 120° with respect to the other. In order to satisfy both the wave-vector conditions of Eq. (1) and the scattering condition that requires $\vec{k}$ to equal the

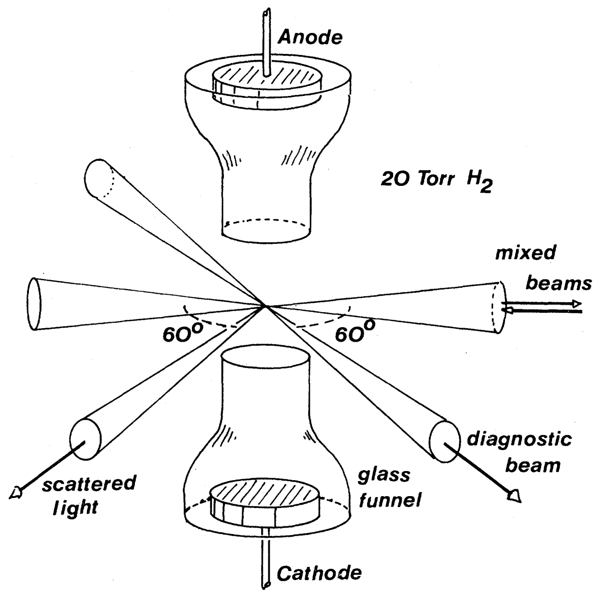

FIG. 1. A schematic view of the arc. The individual light beams are indicated.

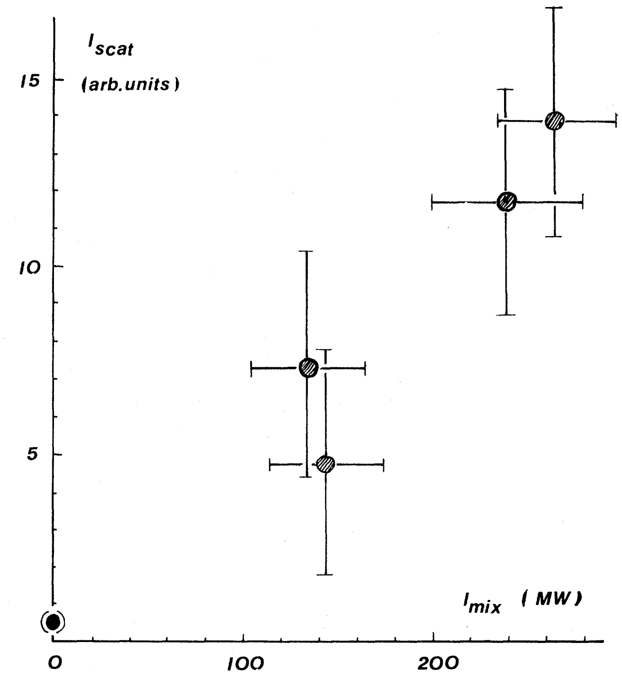

FIG. 2. Scattered light intensity as function of laser power in each of the two mixed beams.

difference vector of incident and scattered wave, scattered light is detected at an angle of 60° with respect to the diagnostic beam. The scattered light is passed through a monochromator of 0.3-Å bandwidth centered on the doubled ruby frequency and then detected by a photomultiplier. The optical arrangement has been described in detail in a Letter investigating enhanced Rayleigh scattering.[4]

The plasma was produced by a pulsed, partially wall-stabilized, hydrogen arc at a filling pressure of 20 Torr. No external magnetic field was present. Figure 1 shows a schematic picture of the arc and also indicates the alignment of the various light beams. The plasma parameters in the mixing volume were investigated in a separate experiment by means of ruby-laser light scattering. The results indicate that the plasma is stable, reproducible, and in local thermodynamic equilibrium with a temperature of 4 eV and an electron density of $n_e = 2\times10^{16}$ cm^{-3}.

Figure 2 shows the experimental results indicating the dependence of scattered light intensity on the power of each of the two mixed beams. The points represent average values derived from at least eight measurements and the error bars represent the standard deviation from the mean. The relatively large errors are caused by the strong plasma continuum radiation in the ultraviolet spectral region which is superimposed on the scattered light signal. This background radiation originates in the extended cooler plasma region surrounding the mixing volume, through which the scattered light must be observed. The magnitude of this plasma noise in fact made measurements of the scattered light intensity at zero mixing-beam power unreliable. Instead this point, indicating the magnitude of the thermal fluctuations, has been calculated from Rayleigh scattering measurements with molecular hydrogen at 50 and 100 Torr filling pressure in the arc vessel.

The results indicate an enhancement of scattered light intensity by a factor of about 30 as the mixing-beam power is raised from 0 to 250 MW. Calculations based on considerations presented earlier[1] predict an enhancement of the same magnitude for parameters (e.g., $\alpha = 0.5$) encountered in the present experiment. The large errors do not allow an accurate comparison of the observed dependence of scattered light intensity on mixing-beam power with the predicted quadratic dependence. One may only conclude that the results do not contradict this dependence. As this present experiment is an exact analogy to the laser fusion case where incident and specularly reflected laser waves mix in the plasma atmosphere in front of a target, the results provide a direct indication that at the higher powers encountered in such studies the effect of nonlinear electromotive forces will be significant.

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Observation of Non-Maxwellian Electron Distribution Functions in the Alcator Device by Means of Thomson Scattering and Their Interpretation*

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In the Alcator device incoherent Thomson scattering always gives Gaussian spectral profiles at low values of the ratio of electron drift velocity to thermal velocity ($v_D/v_{\text{th}} \lesssim 0.1$). However, at higher values of v_D/v_{th} non-Gaussian profiles are observed and can be interpreted in terms of scattering from electrons with high toroidal velocity (low-energy runaways). This interpretation is supported by soft-x-ray and plasma-resistivity measurements and agrees with a previous theoretical analysis.

The Alcator device[1,2] can produce plasma discharges with high values of v_D/v_{th} even at relatively low toroidal current and high plasma density. Typically $v_D/v_{\text{th}}=0.3$ for $I=100$ kA and $\bar{n}=2\times10^{13}$ cm^{-3}. In this machine incoherent 90° Thomson scattering is effected by sending in the laser beam vertically and collecting scattered radiation radially[3]; therefore, the scattering vector[4] $\vec{k}$ is in the meridian plane and only the distribution of transverse velocity is measured as shown in Fig. 1. Indeed, if v_k is the velocity component parallel to $\vec{k}$ and v_T and $v_\perp$ are the two other orthogonal velocity components and if the electron distribution function is $f(v_k, v_T, v_\perp)$,

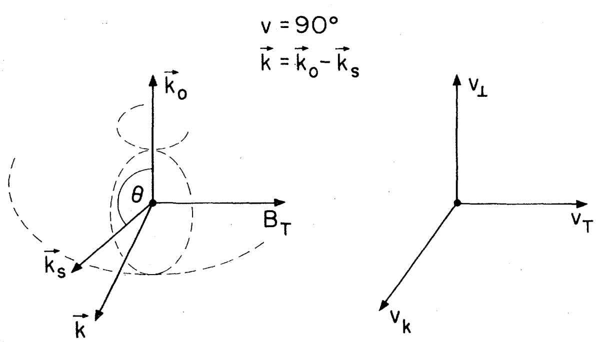

FIG. 1. Scattering geometry for the Alcator device ($\vec{k}_0$, incident light vector; $\vec{k}_\perp$, scattered light vector), and phase space.

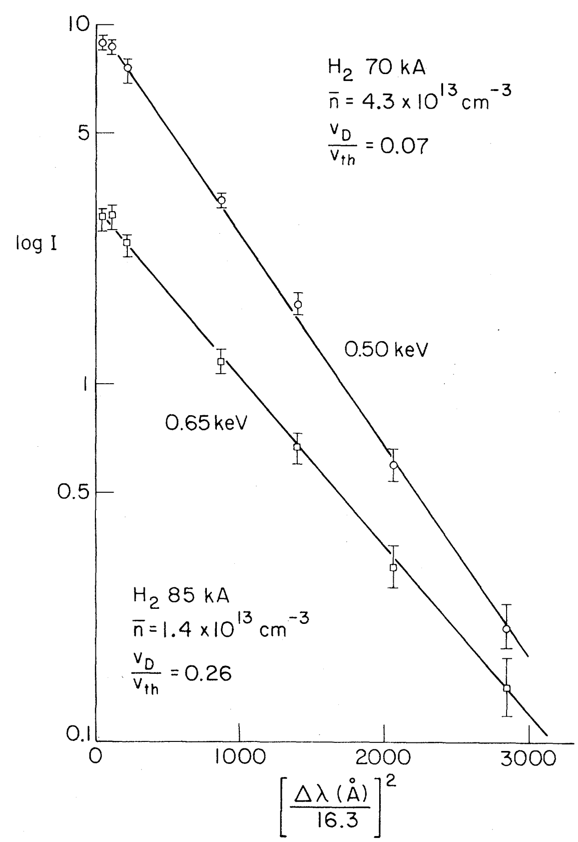

FIG. 2. Spectra of scattered radiation measured at times during the discharge ranging from 15 to 50 msec.