

Resonance Absorption of a Wavelength-shifted Probe Beam in a Laser-Produced Plasma

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The resonance absorption of a weak probe beam in a plasma, produced by $0.53\ \mu\text{m}$ laser irradiation of planar targets at $10^{14}\ \text{W}/\text{cm}^2$, has been investigated. The probe beam ($\lambda = 1.06\ \mu\text{m}$) could be delayed in time relative to the $0.53\ \mu\text{m}$ pulse. Thus a shift of the resonance absorption maximum towards smaller angles of incidence for increasing time delays was found. This is expected on account of the hydrodynamic expansion.

The absorption of intense laser radiation in dense hot plasmas is a central problem in laser fusion experiments. Of particular interest is resonance absorption since it is independent of the intensity and wavelength of the laser, and is effective even in a collisionless plasma. Resonance absorption has been observed at a number of wavelengths: at $1.06\ \mu\text{m}$ [1–2] and $0.53\ \mu\text{m}$ [2], and more recently at $0.26\ \mu\text{m}$ [3] and $10.6\ \mu\text{m}$ [4]. A common feature of all these experiments was that maximum absorption occurred for angles of incidence between 20° – 30° . According to the theory [5] this corresponds to a scale length L at the critical density of one vacuum wavelength, $L \approx \lambda_0$. It is generally believed that such a steep density gradient results from profile steepening by radiation pressure. This implies that resonance absorption at high intensities is complicated by other processes occurring simultaneously.

In order to isolate the basic mechanisms it is therefore highly desirable to investigate resonance absorption under less complex conditions. In this paper we report for the first time an experiment where plasma production and heating has been separated from the investigation of the resonance absorption process. For this purpose we have investigated the angular dependence of a weak, wavelength shifted ($1.06\ \mu\text{m}$) probe beam in the plasma formed by an intense laser beam ($0.53\ \mu\text{m}$). In this manner we can not only eliminate high intensity effects, but also the absorption mechanism under investigation takes place in an (underdense) region

of the plasma which is presumably less complicated than the critical density region of the main laser itself. In addition we could delay the probe pulse relative to the main laser pulse and observe the influence of the changing plasma gradient on the angular dependence of resonance absorption.

We produced the plasma with a $0.53\ \mu\text{m}$ wavelength laser beam of intensity $1 - 3 \times 10^{14}\ \text{W}/\text{cm}^2$. The pulse duration was 30 ps. On the same axis a weak probe beam of wavelength $1.06\ \mu\text{m}$ and 30 ps duration was focussed, with an intensity of $5 \times 10^{10}\ \text{W}/\text{cm}^2$. At this intensity no effects due to radiation pressure and only negligible heating would be expected. The probe pulse could be delayed in time relative to the main pulse up to 100 ps.

The experimental set-up is shown in Figure 1. The $1.06\ \mu\text{m}$ laser beam is converted in a KDP type

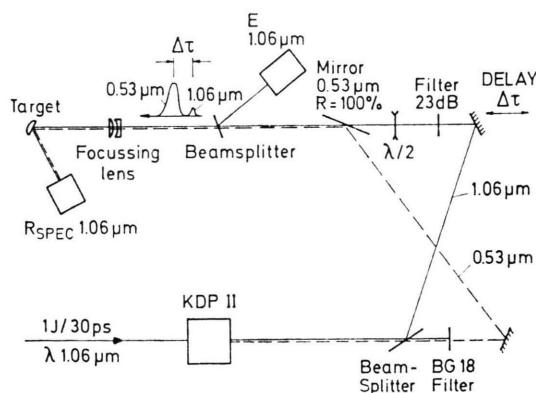


Fig. 1. Schematic diagram of the probe-beam experiment. The $0.53\ \mu\text{m}$ beam is produced in the KDP II crystal. Its intensity on target is $1 - 3 \times 10^{14}\ \text{W}/\text{cm}^2$. The $1.06\ \mu\text{m}$ probe beam is delayed in time; its intensity is $5 \times 10^{10}\ \text{W}/\text{cm}^2$.

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II crystal with a conversion efficiency of 35%. The 0.53 μm light is isolated with a BG 18 filter, and it is focussed onto target with an $f/20$, 400 mm focal length achromatic lens to a spot of 80 μm diameter. The average intensity is $1 - 3 \times 10^{14} \text{ W/cm}^2$. The polarization of the beam is 45° to the plane of incidence. After the KDP II crystal 4% of the light is separated by a beam splitter. It is directed along the same axis as the plasma producing beam by a mirror, which can be translated axially to adjust the time delay $\Delta\tau$. The beam is then attenuated by a factor 200. The polarization of the 1.06 μm beam is turned s or p with a $\lambda/2$ plate and the 1.06 μm beam is transmitted through a mirror, which is a 100% reflector for the 0.53 μm beam. It is then focussed with the same lens to a spot of approximately 80 μm . During the experiment great care was taken that both beams were parallel, with a divergence less than 30 μrad ; therefore both foci overlapped with a maximum 10 μm distance between the two centers. The time delay between the 0.53 μm and 1.06 μm pulse was verified by a streak camera of 10 ps resolution.

The angle of incidence was varied between 6° and 60° by rotating the target. As target material we used copper coated mirrors of optical quality. The incident and reflected 1.06 μm energy was measured with p-i-n diodes covered with diffusors and with RG 645 filters to suppress the 0.53 μm light. The reflected light was collected from a solid angle of 7.10^{-2} Sr ; it was verified by additional detectors that outside of this solid angle no significant contribution to the total reflectance occurred (total contribution $< 1\%$). Hence it follows that the plasma layer reflecting the probe beam may be considered as smooth, and that the measured reflectance equals the total reflectance. Calibration of the detector R_{SPEC} was done in situ by firing only 1.06 μm light onto the target (no plasma is produced by the weak probe beam) and measuring the ratio of the detector signals. This defined 100% reflectance, since the reflectivity of the Cu-target was measured to be $\geq 98\%$ for 1.06 μm .

During experiments we checked that the probe beam was reflected from the plasma, and not from the copper surface. For this purpose the highly reflecting copper target was replaced by a glass target, whose reflectivity for the probe beam alone was only 8%. Upon irradiation with the 0.53 μm beam this target showed the much higher plasma

reflectance (up to 70%, see Fig. 2) for the probe beam, identical to that measured for the plasma produced on the copper target.

For the particular choice of the wavelength of the probe beam (interacting with the plasma at one quarter of the critical density N_{cr} of the main laser beam) one might fear complications if the $2\omega_{\text{pe}}$ instability would be excited at $N_{\text{cr}}/4$ by the main laser beam. Since excitation of this instability should result in $3/2 \omega_L$ emission, we have checked carefully the emission of $\lambda = 0.355 \mu\text{m}$ radiation from the plasma. Within the sensitivity of the spectrograph it was not detectable ($E_{0.355\mu\text{m}}/E_{0.53\mu\text{m}} < 10^{-8}$). Therefore we presume that the instability is not excited in our parameter regime (from [6] the threshold for $\lambda = 0.53 \mu\text{m}$, $L = 1 \mu\text{m}$, $T_e = 0.5 \text{ keV}$ is estimated at $I = 2 \times 10^{15} \text{ W/cm}^2$, which is well above our irradiance level).

The experimental results are plotted in Figure 2; the data points are averaged over approximately 10 shots. For different time delays, $\Delta\tau = 15, 55$ and 70 ps between the maxima of the two pulses, the reflectance of the 1.06 μm light was measured for angles of incidence between 6° and 60° (left curves). In the limit of normal incidence ($\vartheta = 0^\circ$) the plane of incidence is not defined, and one cannot distinguish between s- and p-polarization; therefore the reflectance should be identical ($R^s = R^p$), which we have verified explicitly for $\Delta\tau = 55$ ps. For all time delays a clear difference between R^s and R^p is visible for oblique incidence. We attribute this to resonance absorption: to isolate its contribution we have formed the ratio $(R^s - R^p)/R^s$ in the right hand graphs, and fitted it with the theoretical resonance curve taken from [7]. From the fit a value for the density scale length at the critical density (for 1.06 μm) can be estimated: for $\Delta\tau = 15$ ps an angle of maximum absorption of $\vartheta_m = 22^\circ$ is obtained giving a scale length of $L = 0.8 \mu\text{m}$. At $\Delta\tau = 55$ ps maximum absorption is found at $\vartheta_m \approx 12^\circ$ from which $L \approx 4 \mu\text{m}$ is concluded. At $\Delta\tau = 70$ ps the maximum value of $(R^s - R^p)/R^s$ was measured at $\vartheta = 6^\circ$. The measured data no longer allows a definite determination of the angle of maximum resonance absorption, but an approximate fit shown in Fig. 2 corresponds to $\vartheta_m = 9^\circ$ with a scale length of $L = 16 \mu\text{m}$. We have also made a set of measurements with time delay $\Delta\tau = 100$ ps; here the shot-to-shot variation in R^s and R^p was very large, and no reproducible difference

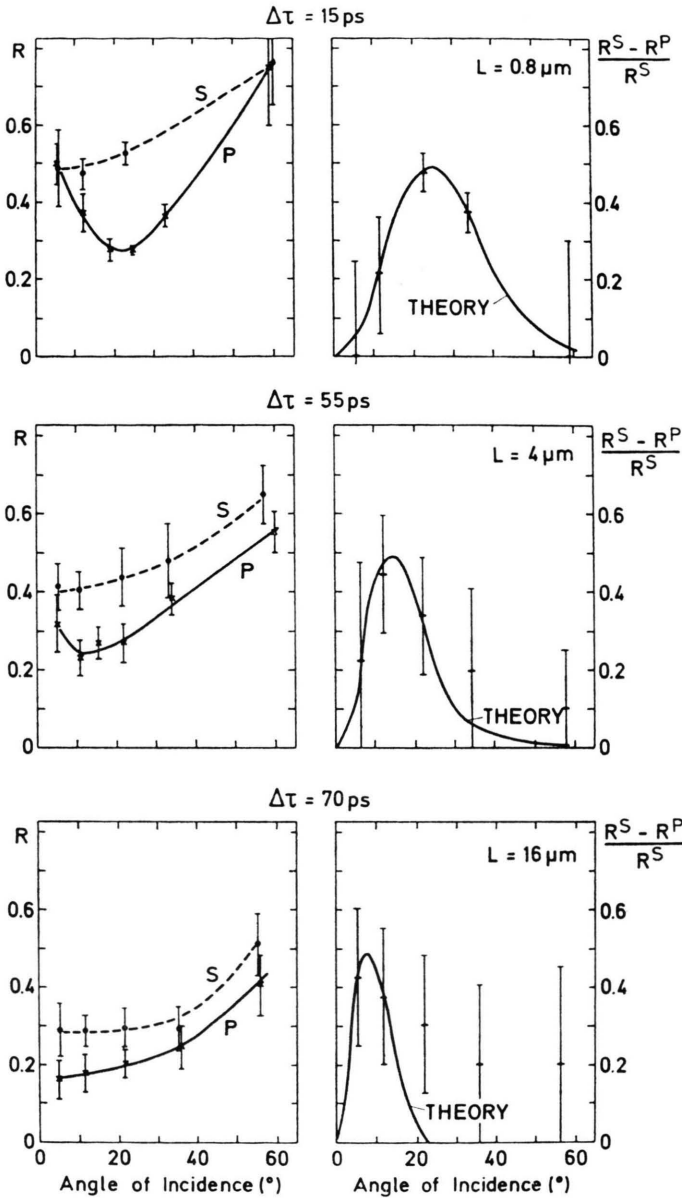


Fig. 2. Reflectance in 7×10^{-2} Sr as function of the incidence angle for s - and p -polarized light and $\lambda = 1.06 \mu\text{m}$ (left); comparison with theory from Ref. [7] (right). Curves are for time delay $\Delta\tau = 15.55$ and 70 ps.

between them was obtainable. This fact is also visible in Fig. 2, where the error bars in $(R^S - R^P)/R^S$ increase for large time delays. The reason for this phenomenon is not clear at this moment, it must be due to the irreproducibility of the plasma conditions at long times after the heating pulse.

From Fig. 2 we see that for $\Delta\tau = 15$ ps the experimental points for $(R^S - R^P)/R^S$ can be fitted excellently by the theoretical curve for resonance absorption. This good agreement suggests that in

this experiment the probe beam is reflected from a smooth plasma. The steep density gradient of $0.8 \mu\text{m}$, obtained from the theoretical fit, is probably not produced by radiation pressure, which should be negligible for the probe beam; rather the steep gradient is simply the result of the limited plasma expansion in 15 ps. Secondly we observe for larger time delays a shift of the resonance absorption curve to smaller angles of incidence. This trend is easily seen from the increasing absorption

at an angle of incidence of $\vartheta = 6^\circ$ with increasing delay time. For $\Delta\tau = 15$ ps we find $(R^s - R^p)/R^s = 0$, for 55 ps it amounts to 0.2, and for 70 ps it is 0.4. Thus we have demonstrated that the resonance function does not necessarily have its maximum at $20-30^\circ$, which was the value found in all past experiments. The theoretical fits in our experiment indicate a scale length L increasing in time; if we model plasma expansion by an isothermal rarefaction wave, the values obtained for L lead to reasonable values for the sound velocity of $1-2 \times 10^7$ cm/s.

In summary we have investigated resonance absorption in a preconditioned plasma with a probe beam, in the limit of weak intensities and without

the complication of previous high intensity experiments. The thus obtained absorption curve confirms the theory for resonance absorption; the observed shift in the absorption curve for increasing time is expected theoretically for plausible plasma conditions.

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