[1] S. Bernabei, M. A. Heald, W. M. Hooke, and F. J. Paoloni, Phys. Rev. Lett. 34, 866 (1975).
[2] P. Bellan and M. Porkolab, Phys. Rev. Lett. 34, 124 (1975).
[3] R. J. Briggs and R. R. Parker, Phys. Rev. Lett. 29, 852 (1972).
[4] P. Bellan and M. Porkolab, Phys. Fluids 19, 995 (1976).
[5] F. Troyon and F. W. Perkins, in Proceedings of the Second Topical Conference on Plasma Heating, Texas Tech University, Lubbock, Texas, 1974 (unpublished).
[6] S. Bernabei, C. Daughney, W. Hooke, R. Motley, T. Nagashima, M. Porkolab, and S. Suckewer, in *Proceedings of the Third Symposium on Plasma Heating in Toroidal Devices, Varenna, Italy, 1976* (Editrice Compositori, Bologna, Italy, 1976), p. 68.
[7] A. Bers, in *Proceedings of the Third Symposium on Plasma Heating in Toroidal Devices, Varenna, Italy, 1976* (Editrice Compositori, Bologna, Italy, 1976), p. 99.
[8] C. Moeller, Doublet IIA Group, and V. Chan, Bull. Am. Phys. Soc. 21, 1053 (1976).
[9] T. M. Antonsen and E. Ott, Bull. Am. Phys. Soc. 20, 1314 (1975).
[10] R. W. Motley, S. Bernabei, W. M. Hooke, and D. L. Jassby, J. Appl. Phys. 46, 3286 (1975).
[11] T. H. Stix, *The Theory of Plasma Waves* (McGraw-Hill, New York, 1962).
[12] R. R. Parker, M. I. T. Quarterly Progress Report No. 102, 1971 (unpublished), p. 97.
[13] J. W. Poukey, J. B. Gerardo, and M. A. Gusinow, Phys. Rev. 179, 211 (1969).
[14] S. Brown, *Basic Data of Plasma Physics* (Wiley, New York, 1959).
[15] G. Morales and Y. Lee, Phys. Rev. Lett. 33, 1534 (1974).
[16] R. N. Franklin, S. M. Hamberger, G. Lampis, and G. J. Smith, Proc. Roy. Soc. London, Ser. A 347, 1 (1975).

Resonance Absorption of 1.06-μm Laser Radiation in Laser-Generated Plasma

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The electron temperature of plasma generated by 35-psec 1.06-μm laser pulses, focused onto perspex targets, has been measured as a function of laser polarization and incidence angle. These measurements demonstrate that resonance absorption contributes significantly to the total absorption of obliquely incident laser radiation. The relative magnitudes of resonance and classical absorption have been measured together with the density of "hot electrons" heated by the resonance process.

A knowledge of the absorption behavior of laser radiation interacting with a laser-generated plasma is important if laser energy absorption is to be optimized for such applications as laser fusion. This is an area of considerable experimental and theoretical acitvity,[1-18] but not all the measurements of absorbed laser energy are in agreement.[1-9] Because of the difficulty of "characterizing" all the relevant experimental parameters these results are not easy to compare. An identification of the relevant absorption mechanisms and the conditions under which they are significant is therefore essential. One such mechanism, which is of topical interest, is that of resonance absorption[10-13]; the laser radiation is absorbed by resonant coupling of its electromagnetic field to Langmuir waves at the critical density surface of the plasma where $\omega_{\text{laser}} = \omega_{\text{plasma}}$. Recent measurements have provided strong evidence for the existence of resonance absorption.[14-18] This Letter describes accurate measurements in general agreement with these results. It is demonstrated that, at intensities of $\sim 2\times10^{13}$ W cm^{-2}, resonance absorption and inverse bremsstrahlung are the dominant mechanisms for the absorption of 1.06-μm, 35-psec, laser pulses, focused obliquely on smooth targets and normally on rough targets.

The experimental arrangement is shown in Fig. 1. A neodymium:yttrium aluminum garnet (Nd:YAlG) ring oscillator generated 35-psec, 1.06-μm laser pulses, in the TEM$_{00}$ mode. These were amplified by a Nd:YAlG/glass chain, which included a discrimination amplifier,[19] to achieve good contrast between the main laser pulse and any background or prepulse noise. The measured discrimination at the output was better than 10^{-6}, so that the laser pulses were "well characterized." They were focused with an $f/3.75$ aspherized lens onto the surface of a plane semi-infinite perspex target where a focal spot diameter of 80 μm was measured. "Smooth target" experiments were made with a surface finish better than $\lambda/4$, and

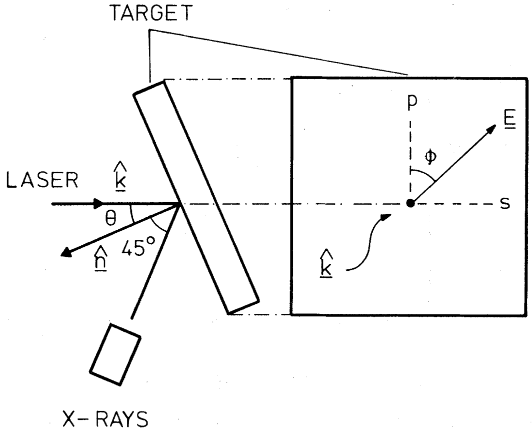

FIG. 1. Experimental configuration.

the massive targets guaranteed surface flatness. The laser beam was passed through a half-wave plate, mounted so that the angle φ between its E vector and the plane of incidence could be set as required.

An output laser intensity I_0 of 2×10^{13} W cm^{-2} was chosen to meet two conditions; (1) inverse bremsstrahlung absorption of less than 30%,[20] (2) I_0 less than the threshold intensities for parametric instabilities. Note that parametric instabilities could significantly affect the absorption, even at oblique incidence.[21]

The normal to the target surface was positioned at an angle θ relative to the incident laser beam axis, and measurements were made for nine different settings of θ ranging from 0° to 40°. The plasma electron temperature was adopted as an indicator of the degree of laser energy absorption. This was measured by the absorber-foil method[22,23] using two absolutely calibrated x-ray detectors (with, respectively, 14.5- and 515-μm-thick Be foils) set at a fixed angle of 45° relative to the target normal. A check was made for isotropy of the x-ray emission relative to the E vector direction which showed that the observation angle was unimportant within the measurement error. The incident laser intensity was kept as close as possible to a constant 2×10^{13} W cm^{-2}, throughout the experiments. X-ray signals were measured as a function of incidence angle θ, for s (E vector orthogonal to incidence plane) and p (E vector in incidence plane) polarizations. For each angle up to ten measurements were made of the absolute x-ray signals on both detectors and these were plotted against the shot-to-shot variation in laser intensity. Two independent values of absolute x-ray intensity were then obtained from the plot at a laser intensity of 2×10^{13} W cm^{-2} and from them two electron temperatures were derived. These were checked for consistency and found to agree within the estimated systematic measurement error. The average of the two temperatures is plotted in Fig. 2(a) together with the systematic error. Note that the major source of error was the uncertainty in plasma volume implicit in the calculation of electron temperature from the measured x-ray intensity. This uncertainty was always less than a factor of 2 which led to an error of between 5% and 10% in electron temperature.

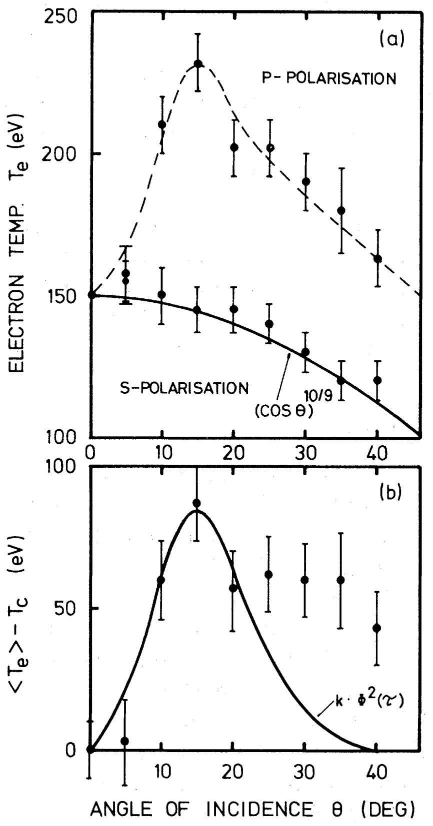

FIG. 2. (a) Measured electron temperature for s and p polarizations, as a function of incidence angle θ. (b) Temperature component due to resonance absorption, as a function of θ.

It can be seen that the s-polarization temperature falls off with the $(\cos\theta)^{10/9}$ variation expected for inverse bremsstrahlung absorption.[17] The p-polarization temperatures indicate a well-defined absorption maximum at 15° ± 5°. A resonance-absorption peak at this angle implies an electron-density scale length $L = 3$ μm, given by $\sin\theta = 0.7(k_0L)^{-1/3}$, in good agreement with the value of L estimated from the measured electron temperature and plasma reflectivity at normal incidence.[20]

Assuming that the electrons generated by resonance absorption are thermalized in the plasma, the electron temperature measured is given by

$$\langle T_e\rangle=[n_H/(n_C+n_H)]\tfrac{3}{2}T_H+T_C, \tag{1}$$

where T_C is the temperature of the electrons heated classically and n_C is the critical electron density; n_H and T_H are the density and initial temperature of hot electrons, respectively. T_H is equivalent to the potential energy gained by a resonant electron:

$$T_H=eE_d\Delta x. \tag{2}$$

Δx is the distance through which the electrons are accelerated and, in this case, where absorption is assumed linear, is taken to be equal to the density scale length L. $E_d=(1-A)^{1/2}E_0\Phi(\tau)(2\pi k_0L)^{-1/2}$, is the electric field which drives the resonance. E_0 is the vacuum electric field, A is the fraction of energy absorbed classically, and $\Phi(\tau)$ is the resonance absorption function taken from Ref. 11. Combining (1) and (2), assuming $n_H\ll n_C$ and $n_H=p\Phi(\tau)I_0^{1/2}$ (p is constant), we find that the temperature component due to resonance absorption is $\langle T_e\rangle-T_C=K\Phi^2(\tau)$; where $K=\tfrac{3}{2}(4e^2L/\omega_0)^{1/2}(p/n_C)(1-A)I_0$. The points $\langle T_e\rangle-T_C$ are plotted in Fig. 2(b) as a function of θ; T_C is taken to be the temperature measured for the s polarization. The continuous line in Fig. 2(b) represents the function $K\Phi^2(\tau)$, and for $L=3$ μm, a good fit to the data points, between 0° and 20°, is obtained when $n_H/n_C=0.02$ at maximum absorption. This value represents a measure of the initial hot- to cold-electron ratio and is in agreement with the value predicted by a numerical simulation for similar conditions in Ref. 11. Note that the deviation of the fit at large angles implies that an additional, weaker, absorption mechanism may be present.

Figure 3 shows the measured electron temperature as a function of E-vector angle φ, at a fixed angle of incidence of 15°. The $\cos^2$ function represented by the continuous line is seen to be a good fit to the data. This clearly demonstrates the presence of resonance absorption, because, with a constant inverse bremsstrahlung contribution, the temperature due to resonance absorption should vary as the square of the E-vector component in the plane of incidence, given by $E_0{}^2\cos^2\varphi$.

At the laser intensities necessary for fusion, processes such as resonance absorption are important. In this application the targets will be strongly curved with no unique angle of incidence. Although curvature allows some absorption,[24] a further increase may be desirable. An attempt was therefore made to cause absorption independent of incidence angle by roughening the target surface. Randomly rough surfaces were prepared, with an average modulation depth and a periodicity of the order of the measured density scale length of 3 μm; the modulation insured that some of the radiation was obliquely incident. The absorption was now found to be insensitive to s or p polarization, with the target angled at $\theta=15°$. Absorption at $\theta°$ was found to be equal to that at 15° and the measured electron temperature, in this case, was 230 eV, equal to that obtained with smooth targets at the optimum incidence angle. This implies that resonance absorption at normal incidence may be possible if the target surface is rough.

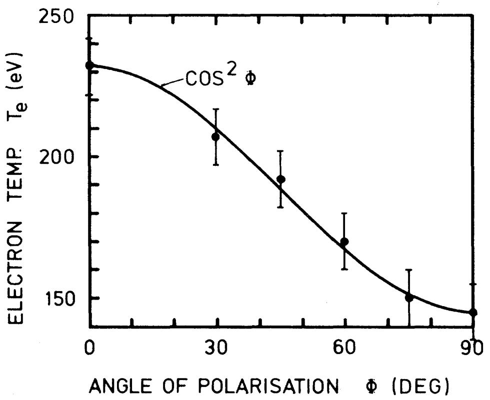

FIG. 3. Measured electron temperature as a function of the angle φ, between the E vector and the incidence plane.

The value of L measured here agrees with that expected for a density gradient determined by hydrodynamic expansion: $L\sim t(ZT_e/m_i)^{1/2}$, where t is the laser pulse length. Comparing this result with those reported for higher laser intensities it can be seen there that the derived density scale lengths are ~4 times shorter than expected on the basis of an uninhibited expansion. This may therefore imply some profile modification at the higher laser intensities, as suggested in Ref. 13.

It is interesting to note in this context that for plasma generated by a 10.6-μm laser, under similar conditions of $\lambda_0{}^2I_0$ (10^{13} W cm^{-2}), resonance absorption was inferred[9,25] when the laser was at normal incidence, where it would have occurred at the curved critical surface caused in part by the formation of a density cavity[26] (cf. profile modification) and in part by hydrodynamic expansion.

In conclusion, it has been demonstrated that resonance absorption can occur in laser-target interactions at oblique incidence. The measurements agree well with theoretical predictions for the behavior of resonance absorption and a value of 2% for the ratio of hot to cold electrons has been derived from the data. It has been shown that, with specially prepared rough surfaces, absorption can be increased, at normal incidence, probably due to resonance effects.

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[1] R. A. Haas, W. C. Mead, W. L. Kruer, D. W. Phillion, H. N. Kornblum, J. D. Lindl, D. Mac Quigg, V. C. Rupert, and K. G. Tirsell, Phys. Fluids 20, 322 (1977).

[2] B. H. Ripin, Appl. Phys. Lett. 30, 134 (1977).

[3] E. Fabre and C. Stenz, Phys. Rev. Lett. 32, 823 (1974).

[4] J. Martineau, P. Paranthoën, M. Rabeau, and C. Patou, Opt. Commun. 15, 404 (1975).

[5] C. Yamanaka, T. Yamanaka, T. Sasaki, J. Mizui, and H. B. Kang, Phys. Rev. Lett. 32, 1038 (1974).

[6] K. Dick and H. Pepin, Opt. Commun. 13, 289 (1975).

[7] T. A. Hall and Y. Z. Negm, Opt. Commun. 16, 275 (1976).

[8] P. E. Dyer, S. A. Ramsden, J. A. Sayers, and M. A. Skipper, J. Phys. D 9, 373 (1976).

[9] T. P. Donaldson, M. Hubbard, and I. J. Spalding, Phys. Rev. Lett. 37, 1348 (1976).

[10] K. G. Estabrook, E. J. Valeo, and W. L. Kruer, Phys. Fluids 18, 1151 (1975).

[11] D. W. Forslund, J. M. Kindel, K. Lee, E. L. Lindman, and R. L. Morse, Phys. Rev. A 11, 679 (1975).

[12] M. M. Mueller, Phys. Rev. Lett. 30, 582 (1973).

[13] R. P. Godwin, Phys. Rev. Lett. 28, 85 (1972).

[14] J. L. Shohet, D. B. van Hulsteyn, S. J. Gitomer, J. F. Kephart, and R. P. Godwin, Phys. Rev. Lett. 38, 1024 (1977).

[15] J. S. Pearlman, J. J. Thomson, and C. E. Max, Phys. Rev. Lett. 38, 1397 (1977).

[16] J. S. Pearlman and M. K. Matzen, Phys. Rev. Lett. 39, 140 (1977).

[17] K. R. Manes, V. C. Rupert, J. M. Auerbach, P. Lee, and J. E. Swain, Phys. Rev. Lett. 39, 281 (1977).

[18] P. Kolodner and E. Yablonovitch, Phys. Rev. Lett. 37, 1754 (1976).

[19] W. Seka and E. Stüssi, J. Appl. Phys. 47, 3538 (1973).

[20] J. E. Balmer, T. P. Donaldson, and J. A. Zimmerman, to be published.

[21] R. B. White, C. S. Liu, and M. N. Rosenbluth, Phys. Rev. Lett. 31, 520 (1973).

[22] F. C. Jahoda, E. M. Little, W. E. Quinn, G. A. Sawyer, and T. F. Stratton, Phys. Rev 119, 843 (1960).

[23] T. P. Donaldson, to be published.

[24] J. J. Thomson, C. E. Max, J. Erkkila, and J. E. Tull, Phys. Rev. Lett. 37, 1052 (1976).

[25] T. P. Donaldson and I. J. Spalding, Phys. Rev. Lett. 36, 467 (1976).

[26] K. Estabrook, Phys. Fluids 19, 1733 (1976).

Properties of Electrostatic Ion-Cyclotron Waves in a Mirror Machine

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Frequency and wavelength of electrostatic ion-cyclotron waves have been measured in a mirror machine. The dominant frequency occurs near the ion-cyclotron fundamental with width $\Delta f/f < 0.02$. For most of the plasma buildup and decay the perpendicular wave numbers are consistent with an ion-diamagnetic drift wave $\omega_i^* = k_\perp (cE_i/cB)(1/n)dn/dx$ at the ion-cyclotron frequency. With increasing wave amplitude the wave spectral properties do not change but an increase in ion energy diffusion is observed, supporting a wave-particle saturation of the mode.

Plasma confinement experiments in minimum-B magnetic mirror machines[1,2] have demonstrated the simultaneous reduction of hot-plasma loss rate and amplitude of ion-cyclotron oscillations with addition of warm streaming plasma injected along magnetic field lines. According to theoretical interpretation of these experiments[3] the streaming plasma stabilizes the drift cyclotron loss-cone[4] (DCLC) instability that is driven by the velocity-space loss cone of the ion distribution and the radial plasma density gradient. In this Letter we report measurements of the frequency and wavelength of the ion-cyclotron oscillations in the neutral-beam-injected *2XIIB* de-