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Evidence of Stimulated Backscattering of
Laser Radiation from a Laser Produced
Plasma ⁺)

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scattering of Laser Radiation
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A b s t r a c t

The reflection of laser light from a laser produced deuterium plasma was experimentally investigated. Strong evidence of stimulated backscattering was obtained.

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One of the basic problems in the production of high-density thermonuclear plasmas by laser radiation is the interaction of the intense light wave with the plasma. In particular, efficient heating can be achieved only if a large fraction of the incident laser radiation is absorbed rather than reflected by the plasma. In this report experimental data on reflection from a laser produced deuterium plasma are presented for a laser wavelength of $\lambda = 1.06 \mu$.

The experimental arrangement is shown in Fig.1. The beam of a multi-stage neodymium glass laser is focussed on the plane surface of sticks of solid deuterium (square cross section $2 \times 2 \text{ mm}$). These targets are produced by a liquid-helium-cooled cryostat at the top of the target chamber [1]. The diameter of the laser beam at the exit of the last amplifier is 60 mm. The beam is focussed with a $f = 75 \text{ mm}$ aspherical lens. The laser pulse length is 5 ns, the pulse rise time about 1.5 nsec. The pulse energy incident on the target was varied between 0.2 and 20 J^+ . In this report we only discuss results obtained with fast photodiodes for detecting the pulse shape and energy of the incident and reflected laser light.

The reflection coefficient varies strongly with the distance of the target from the focussing lens (Fig.2). Typically, the reflection coefficient drops by a factor of two when the target is moved from the optimum position to either side by 150μ . The target position of maximum reflection coincides with that of maximum electron temperature. This results from similar measurements with a carbon target where the electron temperature of the plasma was determined in various positions from the soft x-ray radiation of the plasma.

Fig.3 shows the pulse shape of the incident and reflected laser light for three successive shots as observed on a Tektronix 519 oscilloscope (the delay of about 32 ns being introduced intentionally). As can be seen, the pulse shape of the reflected laser light always closely follows that of the incident light, at least at pulse maximum.

⁺) From preliminary measurements we estimate a focal spot size of $4 \cdot 10^{-6} \text{ cm}^2$ for $E_i/2$; i.e. an intensity of $5 \cdot 10^{14} \text{ W cm}^{-2}$ for $E_i = 20 \text{ J}$

In measuring the dependence of the reflected laser energy on the incident energy, the target position of maximum reflection was determined by a series of shots with an energy of 10 J. Subsequently, the targets were always adjusted to this position; this could be controlled with an accuracy of $\pm 20 \mu$ by imaging the target with 10-fold magnification on a screen. The pulse energy was varied by inserting attenuating filters in the laser beam after the last amplifier stage; the pumping power of the laser was kept constant during the experiments.

Fig.4 shows the reflected laser energy E_r versus the incident energy E_i . For $E_i = 0.2$ J about 8 % of the incident energy is reflected; with $E_i = 20$ J reflection increases to 30 %. Measurements performed in [2] under similar conditions fit closely to our results; they have therefore been included in Fig.4. Then the measurements cover a range of nearly three orders of magnitude of the incident pulse energy. With $E_i = 80$ J reflection increases to 44 %. The dependence of E_r on E_i is quite distinct; it follows the power law $E_r \propto E_i^{1.28}$ over the whole measured range. Clearly, these measurements are not favourable for efficient heating of high temperature plasmas with 1.06μ laser radiation. If the measured dependence continues towards higher pulse energies complete reflection would occur at a laser energy of 1 kJ (at this energy the curve corresponding to complete reflection (dashed line in Fig.4) and the lengthened measured curve would intersect).

These measurements account only for that part of the reflected laser light which goes back through the focussing lens. This raises the question whether a certain amount of energy might be scattered in addition into a larger solid angle than that covered by the focussing lens. For that reason and also in order to obtain more information on the reflection mechanism, we measured the angular distribution of the backscattered light. In a first step we used the arrangement shown in Fig.5. The laser beam was stopped down by means of a circular diaphragm with a diameter of 37 mm, so that the outer zones of the focussing lens (75 mm) could be used to detect the laser light backscattered into angles larger than that of the incident beam. A second diaphragm of variable diameter was then used to scan

the intensity distribution of the backscattered light over the whole diameter of the focussing lens. It is found (see Fig.6) that the backscattered light fills the same cone as the incident light; the contribution of the outer zones of the lens is small.

A more direct method for measuring the intensity distribution of the backscattered light was then applied using the arrangement in Fig.7. A mask was used to stop down the laser beam after the last amplifier stage. Holes of variable shape were cut into this mask and various intensity distributions of the laser light were thus achieved on the entrance window of the target chamber. The intensity distribution on the entrance window (which is the same as on the neighbouring focussing lens) was then photographed simultaneously in the incident and backscattered laser light. Instead of infrared-sensitive photographic plates we simply used sheets of exposed Polaroid film since the high intensity laser beams burn pictures of sufficiently good spatial resolution into the surface of this material.

Fig.8 and 9 shows photographs obtained in this way. Since the distribution of the backscattered light was photographed with the help of a beam splitter it had to be inverted for convenient comparison with this distribution of the incident laser light. This was done in Fig.8 and 9 by photographic means in such a way that both distributions now appear as an observer looking towards the entrance window would see them. A check of this procedure is afforded by a mark in the form of an arrow fixed in front of the entrance window. In Fig.8 the arrow was placed in the upper left part of the window and in Fig.9 in the upper right part of it.

In Fig.8 the mask stopped down half of the beam, so that only the left half of the focussing lens was irradiated. As it appears from that figure, the backscattered laser light also fills only half of the lens, namely that through which the laser light is incident on the target. The other half of the lens remains dark. Examination of the original photographs shows that "hot" spots of high intensity in the incident beam tend to reappear in the backscattered laser light.

In Fig.9 a hole in the shape of a question mark was cut into the mask (the bright spots in the photograph obtained with the incident laser light are due to the inhomogeneous intensity distribution in the laser beam). Though already somewhat detailed, this intensity distribution is also fairly well reproduced in the backscattered laser light. Even the point of the question mark is clearly resolved in the backscattered light.

It is evident from these photographs that in backscattering from our laser plasma each light ray is scattered back upon itself. For this observation as well as for the power law observed for reflection no detailed theoretical model has been worked out so far. Nevertheless it seems useful to discuss in the following two possible explanations of the observed directionality of the backscattering. These are "classical" light reflection from an overdense plasma and stimulated Brillouin backscattering.

Classical reflection from an overdense plasma means that the light is reflected in the vicinity of the layer whose electron density is determined by the condition $\omega_p = \omega_L$ (ω_L = laser frequency, $\omega_p = (\frac{n_e e^2}{\epsilon_0 m_e})^{1/2}$ = plasma frequency. For $\lambda = 1.06 \mu$ laser radiation the corresponding electron density is $n_e = 10^{21} \text{ cm}^{-3}$). To illustrate the situation in the case of a laser plasma, a schematic sketch of the plasma flow is presented in Fig.10. A crater preceded by a compression wave will form in the target during irradiation. Under our experimental conditions its depth will typically be a few hundred microns at the end of the 5 ns laser pulse. The plasma is produced in the interior of the crater and rapidly expands towards the vacuum. The reflecting layer will be located somewhere between the compression wave and the vacuum; its structure will determine the angular distribution of the backscattered light in this model.

Since the position and curvature of the reflecting layer are not known from the experiment and can probably be predicted only by two-dimensional computer simulation of the gasdynamic flow, let us discuss two hypothetical cases (Fig.11):

- a) If the reflecting layer constitutes a plane mirror, then a light ray going through one half of the focussing lens should be reflected through the other half of it (Fig.11a). This does not correspond to the experimental result (Fig.8).
- b) If the reflecting layer constitutes a curved mirror, then the cone of reflected light would, in general, be narrower or wider than that of the incident beam, depending on the relative position of the focal spot of the lens and the center of curvature of the plasma mirror. Only if those two points coincide (Fig.11b), would each light ray be reflected back upon itself, as is observed in the experiment.

However, it seems very unlikely to us that such a classical explanation can account for the experimental results. It is hard to imagine that, irrespective of the intensity distribution in the plasma producing laser beam, such a tiny, but precise mirror always forms in the plasma, and that, furthermore, it remains exactly centered relative to the focal spot during the whole pulse length. In addition, this should occur not only for a deuterium, but also for a carbon target ⁺), where one would expect the gasdynamic flow and the structure of the reflecting to be somewhat different. These difficulties do not exist if we interpret the observations in terms of stimulated Brillouin scattering.

It is well known that stimulated Brillouin scattering can lead to backscattering of more than 90 % of the incident laser radiation in liquids /3/. The underlying physical mechanism is the decay of the incident electromagnetic wave into a sound wave and a second electromagnetic wave which is amplified in the backward direction. In a plasma, coupling between the waves may occur by the $\mathbf{v} \times \mathbf{B}$ force which acts on the oscillating plasma electrons in the magnetic field of the electromagnetic waves /4/. In this process the directional character of the backscattering is readily explained since the backscattered electromagnetic wave is most strongly amplified along

⁺) Recent observations with a carbon target show the same behaviour of the backscattered laser light as demonstrated in Fig.8 and 9.

the incident laser light wave. It is not necessary in this case for the plasma to have a very special structure. We therefore consider stimulated Brillouin scattering to be a much more likely explanation of the experimental results than classical light reflection.

It is obvious that the nature of the backscattering may be further determined by spectral analysis of the backscattered laser light with respect to possible wavelength shifts. Such an investigation has already been made in this experiment under similar conditions to those here /5/. A red shift of several angstroms was measured (2.5 \AA in Fig.12). As was discussed in /5/, this wavelength shift may be explained in terms of classical reflection from the reflecting layer, which moves into the interior of the target as a result of crater formation. Though this effect may be important for a final interpretation of the measured data, the observation of directed backscattering makes this interpretation no longer entirely satisfactory. In fact the observed wavelength shift can also be explained in terms of stimulated Brillouin scattering. In the case of a homogeneous plasma at rest a red shift of the backscattered light by an amount

$$\Delta\lambda = 2\lambda n v_s / c$$

is expected. With a velocity of sound of $v_s = 2 \times 10^7 \text{ +)}$ we obtain $\Delta\lambda = 2.5 \text{ \AA}$ by assuming an index of refraction for the incident electromagnetic wave of $n = 0.18$. Evaluation of $\Delta\lambda$ in this way is, however, only a formal procedure which mainly indicates that the direction and order of magnitude of the wavelength shift is as expected from Brillouin scattering. A quantitative description must take into account the strong density gradients in the plasma (n varies in the range $0 < n < 1$ between the reflecting layer and the vacuum) and, in particular, the streaming of the plasma towards the vacuum. Such

+) Attempts have been made to measure the electron temperature in the plasma from its soft x-ray radiation /6/. These measurements are complicated by non-thermal hard x-ray radiation from the plasma. However, the electron temperature is estimated to be 500 eV or somewhat less. Assuming $T_e = 500 \text{ eV}$ and $T_i \ll T_e$ then yields $v_s = 2 \cdot 10^7 \text{ cm s}^{-1}$.

an analysis as well as systematic measurements of reflection coefficients and wavelength shifts for different target materials are underway. It should be stressed, however, that a complete picture of light-plasma interaction in this experiment may be fairly complicated since it should account also for other observations made in this experiment. These are the generation of the harmonic of laser light ($\lambda = 5300 \text{ \AA}$) and the emission of hard x-ray radiation /6/, runaway electrons /7/ and groups of fast ions /6/ from the plasma.

To summarize, it has been shown that the plasma investigated here shows quite distinct and reproducible behaviour with respect to backscattering of laser light. In particular, the dependence of the backscattered laser energy on the incident energy follows the power law $E_r \propto E_i^{1.28}$, and the incident light rays are always found to be backscattered in the same direction. No attempts have been made so far to provide a quantitative explanation of these observations; nevertheless the directional character of the backscattering is believed to afford strong evidence that stimulated Brillouin scattering is important in this experiment.

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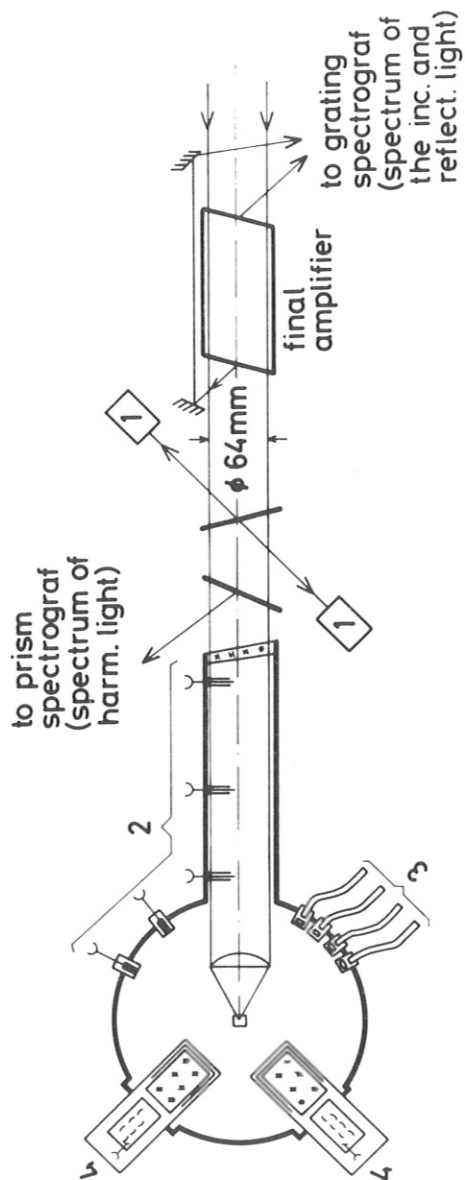


Fig. 1 Experimental arrangement: 1. fast photodiodes for detecting incident and reflected laser light. 2. set of probes for ion detection. 3. detectors for soft x-ray emission from the plasma. 4. neutron counters

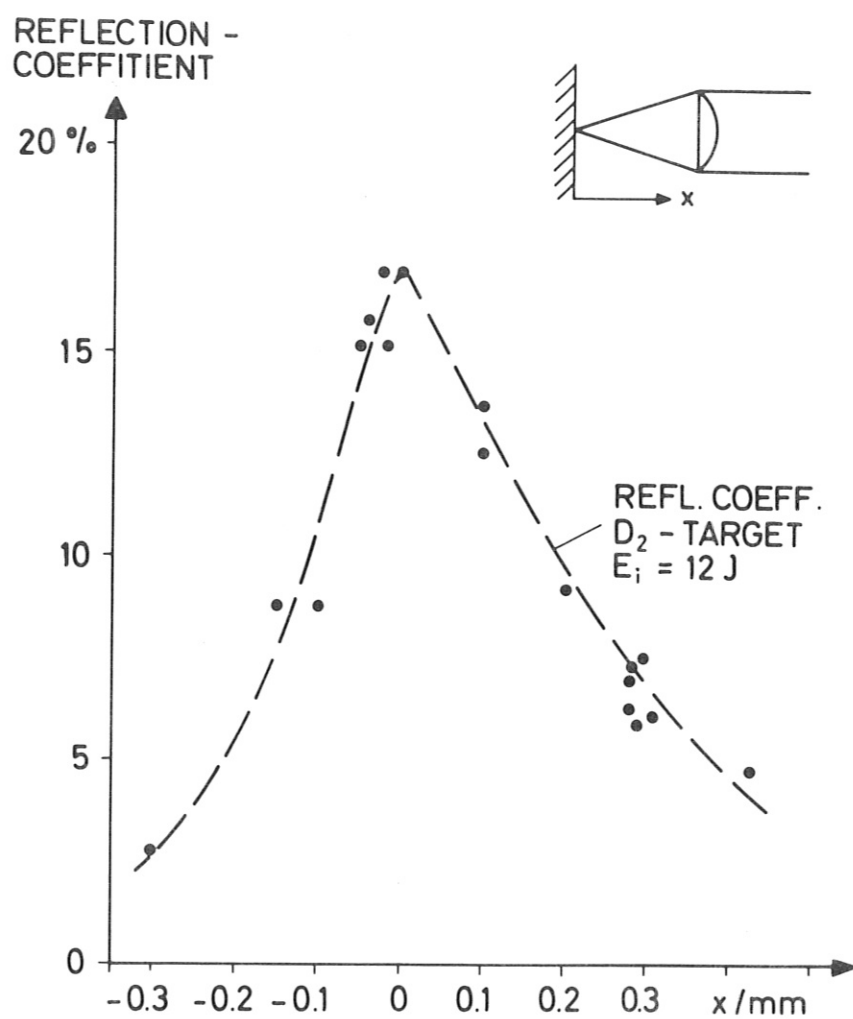


Fig. 2 Reflection coefficient versus position of the target

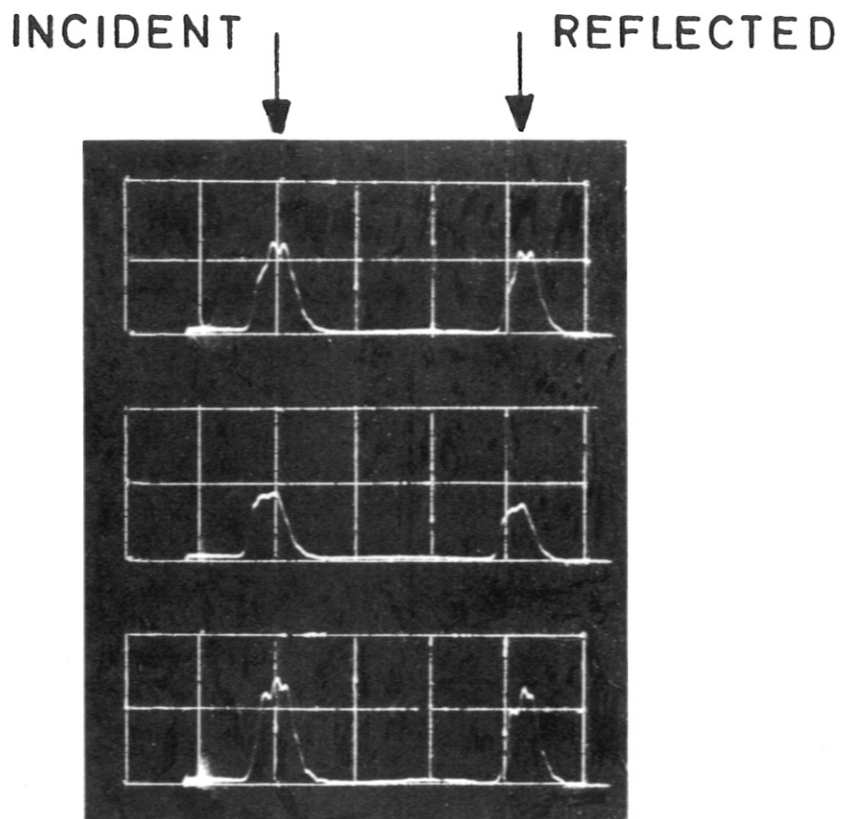


Fig. 3 Incident and reflected laser pulses (note: the sensitivities of the two photodiodes are different). Time scale 10 ns/div.

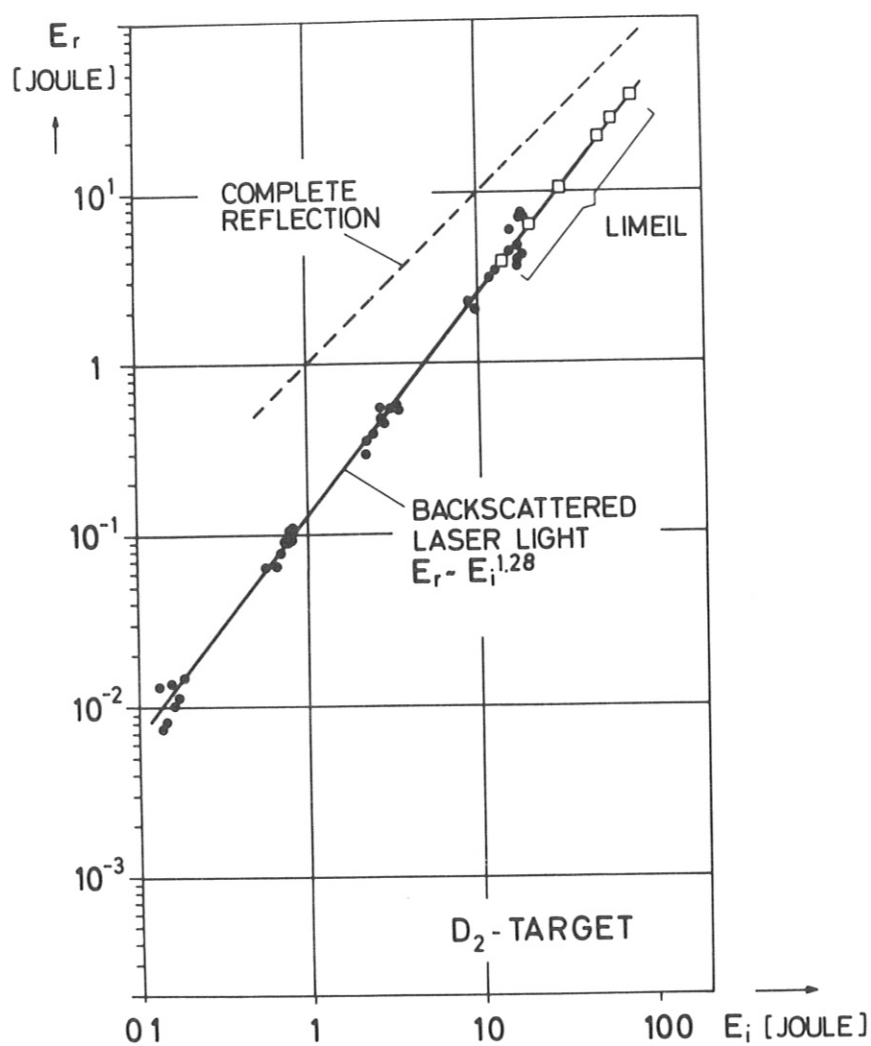


Fig. 4 Reflected versus incident laser energy

ANGULAR DISTRIBUTION OF BACKSCATTERED LIGHT

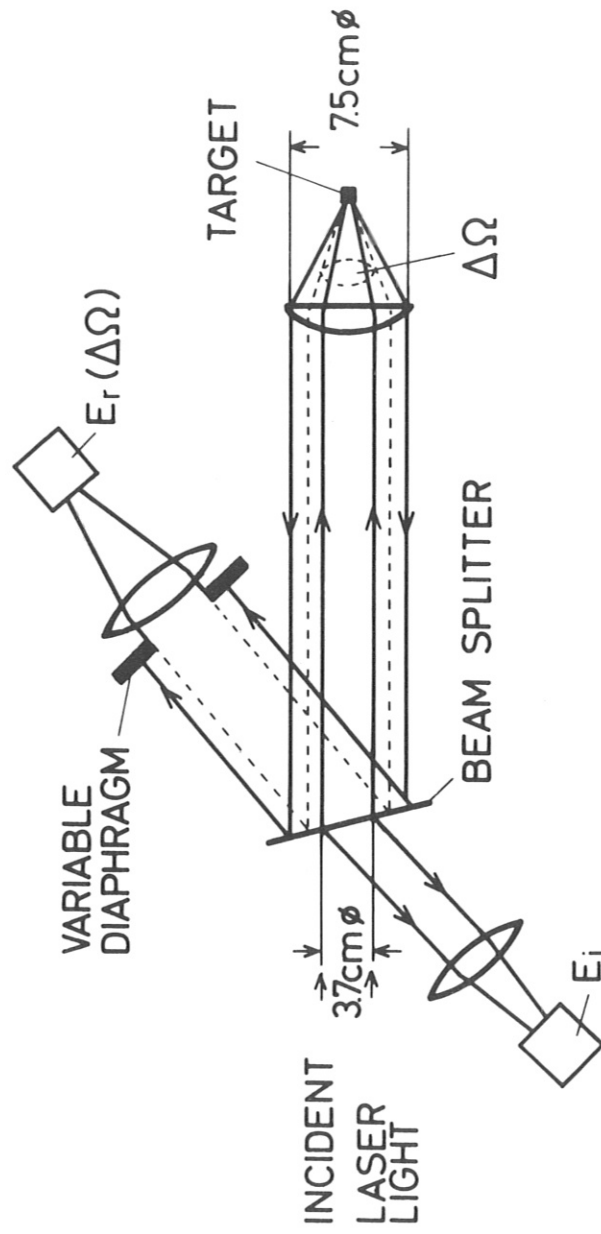


Fig. 5 Set-up for measuring the angular distribution of the back-scattered laser light.

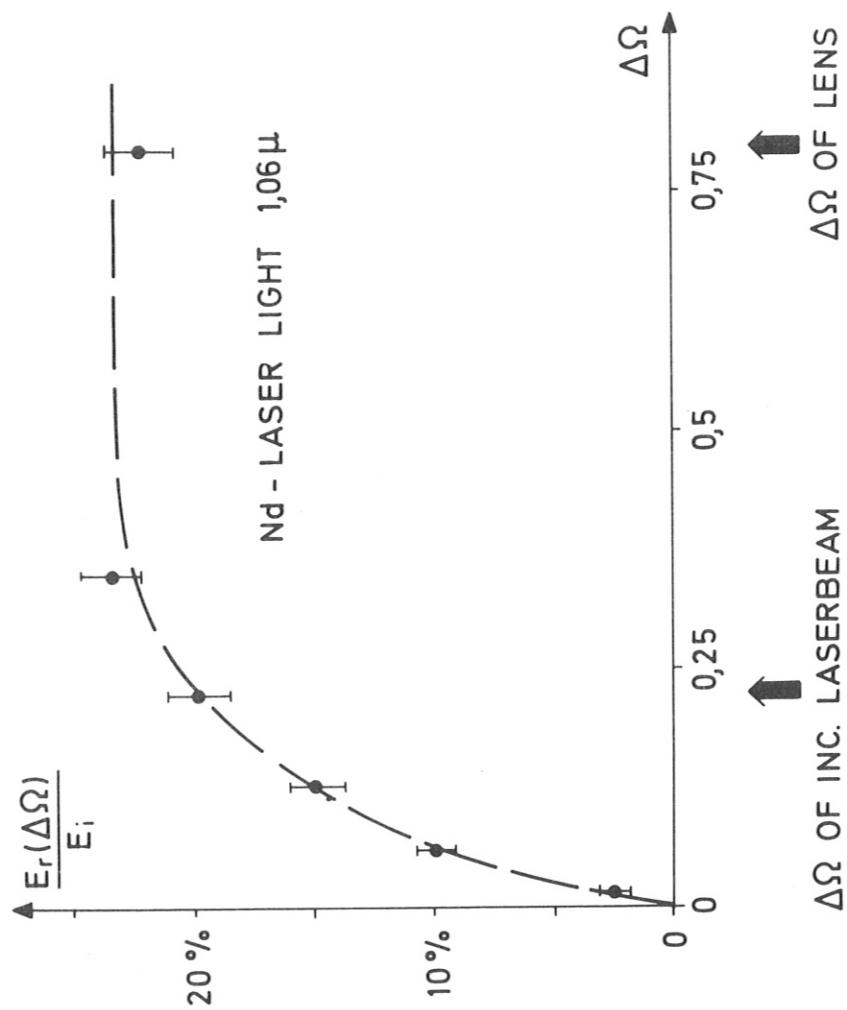


Fig. 6 Fraction of backscattered laser light energy, integrated over the solid angle

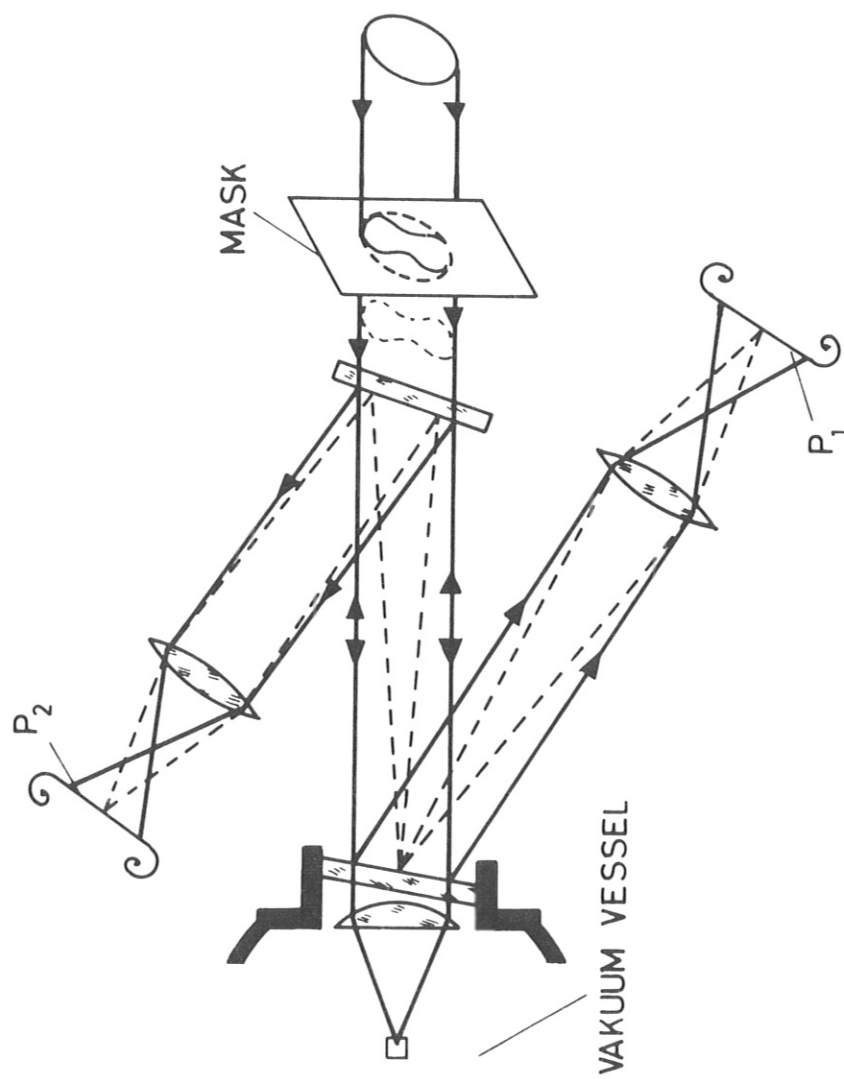
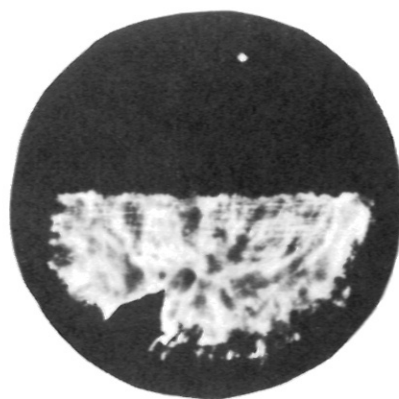
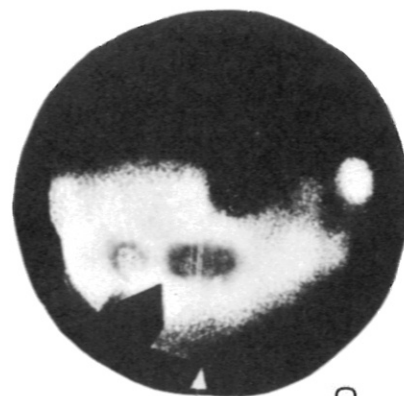


Fig. 7 Set-up for photographing the intensity distribution of incident (P_1) and backscattered (P_2) laser light on the entrance window of the test chamber



INCIDENT



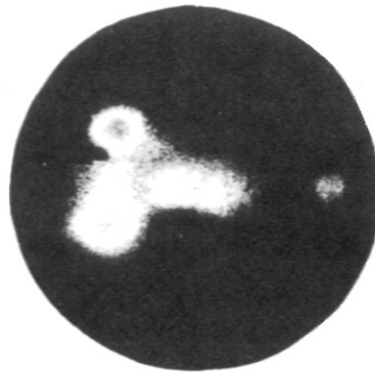
EDGE OF
LENS

REFLECTED

Fig. 8 Photograph of the distribution of incident and reflected laser light over the focussing lens. The right half of the incident beam was stopped down with a mask.



INCIDENT
MASKED BEAM



REFLECTED

Fig. 9 Photograph of the distribution of incident and reflected laser light over the focussing lens. A mask with a hole in the shape of a question mark was put into the incident beam.

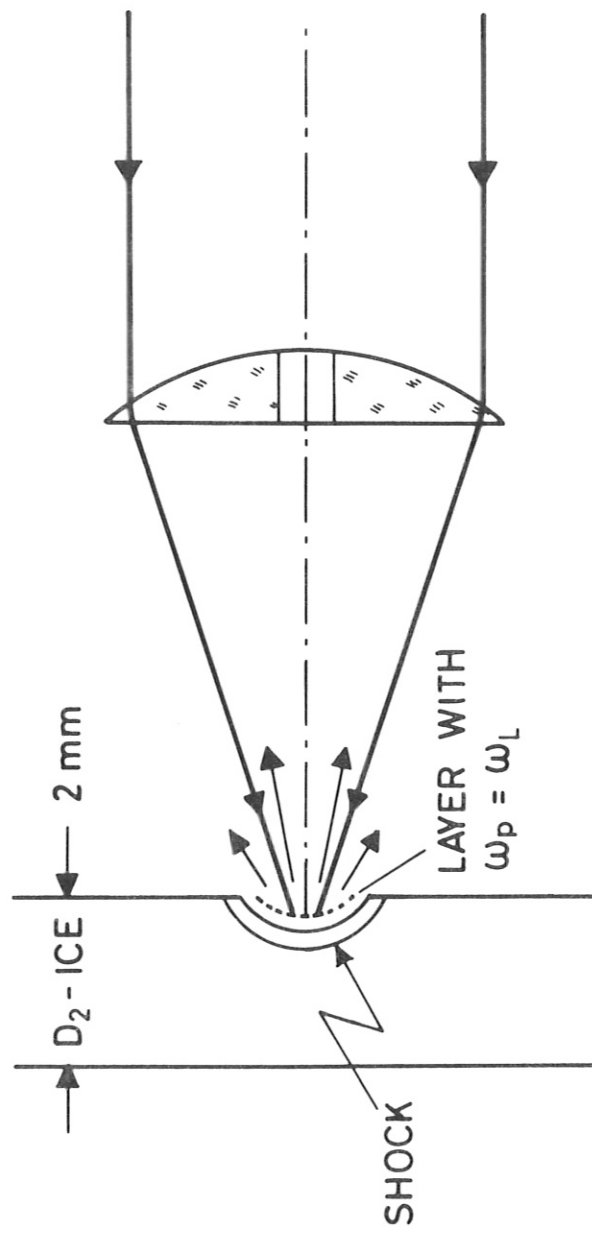


Fig. 10 Sketch of plasma flow in the experiment

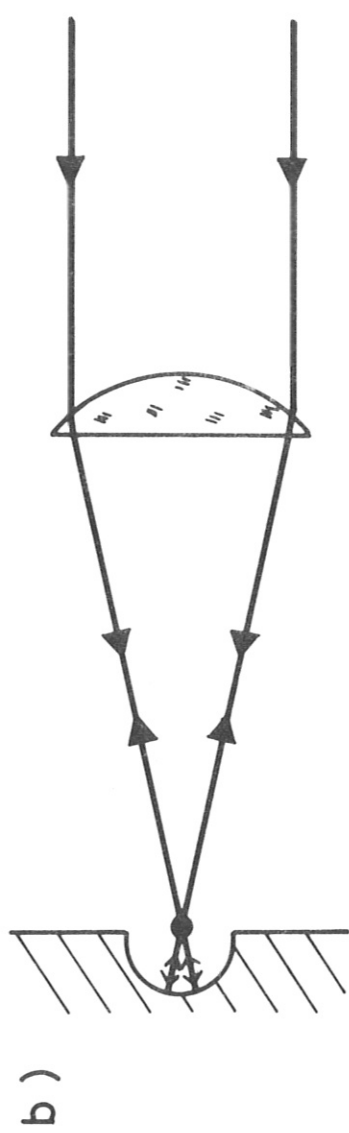
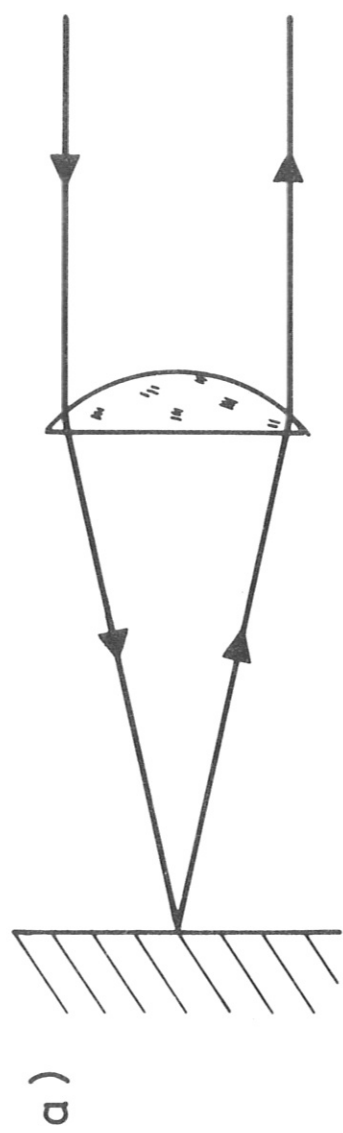


Fig. 11 Path of light rays in the case of a plane mirror (a) and a curved mirror (b)

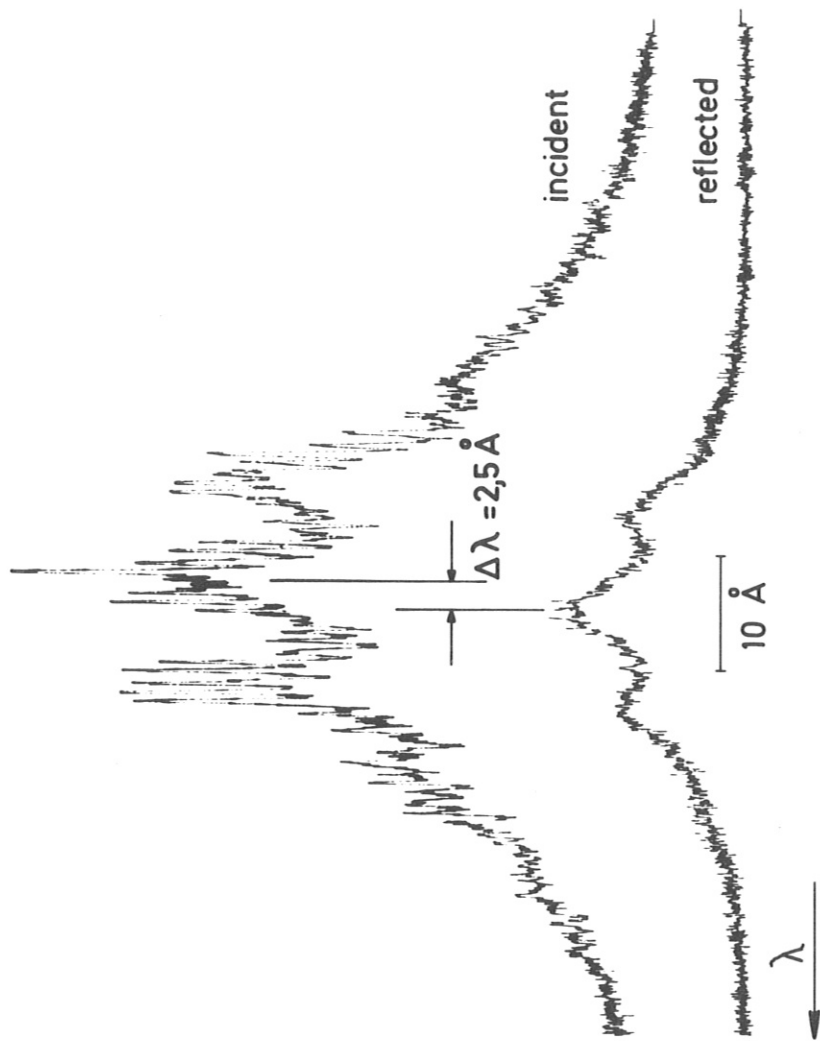


Fig. 12 Spectra of incident and backscattered laser light /5/