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Production of Plasma with a CO_2-TEA-Laser from Solid Hydrogen Targets

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Abstract

A hydrogen plasma is produced with a CO_2-TEA-laser of about 1 MW power. The plasma is investigated with probes, streak and short time photography, transmission measurements, holographic interferometry and shadowgrams with a ruby laser. The measurements are compared with a theory of plasma production by laser from solid targets and good agreement has been found also for 10.6 μ laser radiation. Recombination is found to be important in this experiment.

Introduction

Hitherto, for the production of plasma from solid hydrogen and deuterium, Ruby- and Neodymium-Lasers have been used /1, 2, 3, 4, 5/. With the development of the TEA-laser by Beaulieu and his coworkers /6, 7/, plasma production with 10.6 μ laser radiation was become possible. In several publications the gas break-down produced by a pulsed CO_2-laser has been investigated /8, 9, 10, 11/. Gibson et. al. /12/ observed plasma production on solid surfaces by focusing a Q-switched CO_2-laser on it. They report spectra of multiply ionized atoms. Only a rough description of the plasma formation process is given.

In this article, for the first time, plasma production from a solid hydrogen target by a CO_2-laser with high pulsed power is reported. In the first section the CO_2-laser will be described. The experimental set up and results will be given in the following sections. In section IV the measurements will be compared with the theory, and with previous results of plasma production by Ruby lasers.

I. TEA-Laser

To get a Megawatt-CO_2-laser, the number of active molecules in the gaseous laser medium has to be increased, compared to the normal cw CO_2-laser /6/. Increased gas pressure requires higher voltages for the electrical discharge to occur. The voltage ranges up to a Megavolt, if the discharge is parallel to the laser beam /13/. In the case of transverse exitation, voltages of several tens of kilovolt are sufficent. Different lasers of this transverse exitation type are described in /6, 7, 14, 15, 16, 17/.

For the experiment to be described we built a TEA-laser with electrodes arranged along a helix (fig.1). The laser has dimensions as follows: length = 4 m, diameter of the discharge tube = 60 mm and the electrodes = 25 mm. A resistor of 1.2 KΩ is connected in series with each of the nearly 5oo discharges. The distance between neighbouring discharges is 8 mm. The power supply for all discharges consists of a capacitor of 25 nF, charged up to 3o KV. It is triggered by an electrical spark gap. The resonator mirrors are fixed at the ends of the plexiglas tube in adjustable mounts. The resonator consists of one concave gold mirror (R = 11 m) with 1oo % reflectivity and one plane germanium mirror with 65 % reflectivity. The active gas is a mixture of 5 % CO_2, 5 % nitrogen and 9o % helium. The gas pressure is about one atmosphere. The gas streams out of the discharge tube into the atmosphere through a small hole in the tube. A photograph of the laser and vacuum cell for plasma production (on the left) is seen in fig.2. The power supply charging the capacitor limits the repitition rate to one shot in 5 sec^{-1}. Between the beginning of the discharge and the laser radiation there is a delay of 1 - 3 μsec.

The energy of the laser pulse has been measured to be o.2 - o.3 Joules, using a cone calorimeter. During the measurement in the cone a spark can be observed and also a sharp crack can be heard. The observations are similar to those in gas breakdown or plasma production on targets by laser irradiation. If the absorption coefficient for 1o.6 μ radiation is taken in consideration, which is lower than that for 1 μ, it can be assumed that the energy is concentrated mainly in the tip of the cone and plasma is created. Part of the radiation leaks out of the cone too. Consequently the measurement determines only the lower limit of the output energy of the laser. The exact energy as measured with a liquid calorimeter for 1o.6 μ /29/ is greater by a factor of about two. The pulse shape has been measured with a gold-doped germanium detector (Philco, type GPC 216). The intensity was reduced by scatterplates made of rocksalt. The detector circuit is shown in fig.3. The overall time resolution is about 1o nsec. We can discern in the laser pulse two parts depending on the gas mixture (fig.12); an initial pulse with half width of 25o nsec and a peak power of about 1 MW, followed by a slow decay of 2 - 5 μsec and a mean power of a few hundred KW. Very often self mode locking can be observed in the laser pulse /9/. The width and amplitude of the very short pulses due to mode locking could not be determined.

The divergence of the laser beam (diameter 5 mm) was measured with a germanium mirror of 1o m focal length and an infrared detector (fig.4). The beam divergence was determined to be 1.1 mrad. This is very near to the diffraction limit, which is 1.o mrad for a beam with the same diameter.

II. Experimental set up

The various methods employed for the observation and diagnostics of the laser produced plasma are shown in fig.5. The cryostat for the production of H_2-targets is described in /2/.

The laser beam is focused on to the solid hydrogen target by a rocksalt lens of focal length of 5 cm. The diameter of the focal spot results from the beam divergence. It was calculated to be 11o μ. We assume a mean laser power of o.5 MW; that is equivalent to a radiation flux of $5 \cdot 1o^9$ W/cm^2 on the surface of the target.

The adjustment of the distance between the lens and the target is done with the aid of gas break-down produced in the chamber filled with air, and with the same CO_2 laser. As described in /8, 9/ a forward growing filament starts at the focus of the beam. By observing the starting point of this filament either by eye or short time photography the focal point can be determined exactly. The lens is adjusted until the focus is situated in the same plane where the hydrogen target will be grown.

A part of the incident laser beam is deflected by a silver mirror into an ir-detector. The absorption of metal surfaces for 1o.6 μ is low, so the unfocused beam does not destroy the mirror. Intensity in the edge of the laser beam is recorded this way (fig.5). After each shot this measurement is cross-checked with the measurement of intensity in the center of the laser beam using another ir-detector. Also the radiation transmitted through the hydrogen target is measured by an ir-detector.

An image converter camera has been used in streak and short time photography regimes for the investigation of the plasma. Ion probes biased to - 3o V are located at several points in the vacuum cell.

For holographic interferometry and shadowgrams of the expanding gas or plasma a ruby laser was operated synchroniously with the TEA-laser. The ruby laser was Q-switched by a Pockels-cell and emitted a light pulse of 2o nsec duration at a controlled time. Coincident with the ruby laser emission a time mark was added to the detector signal of the CO_2-laser. Shadowgrams too were taken with the Ruby laser. The optical arrangement is not shown in fig.5.

III. Results

Short time photographs show the production of plasma (fig.6). The target was photographed, transverse to the direction of the laser beam, at various times during the emission of the laser beam. The target is marked in the pictures. Its thickness is 1 mm. The following conclusions can be drawn. The plasma is created at the beginning of the laser pulse on the front of the target. About 1 μsec later, plasma can be observed also on the rear side of the target. A strong emission of visible radiation occurs up to 1 - 2 mm distance from the surface. Contrary to observations in gas breakdown, a luminous front can not be observed. This is confirmed by streak photographs (fig.7). A speed of "burning" through the target can be calculated from streak photographs and from the transmission measurements of the CO_2-radiation. Both methods give a speed of "burning" of $1.1 \cdot 10^5$ cm/s.

Measurements of transmitted laser radiation are shown in fig.8 for different thicknesses of the hydrogen target; up to 2.o mm thickness. At the beginning of the laser pulse the target is transparent. This can be seen from the peak of transmitted light observed at the beginning of the pulse. Then, for a period of about 1 μsec, the target is opaque to the laser radiation. From the thickness of the target and the duration of opacity we calculate a "burn" velocity of o.11 cm/µsec. As in fig.8, very often another minimum of transmitted laser light is observed, which is delayed with respect to the fast rise of the transmitted radiation by 3oo - 4oo nsec. The measurements of the transmitted radiation were done with the same sensitivity of the detector as for the incident light.

Interferograms were made with the holographic double exposure technique with a ruby laser, which was synchronized with the TEA-laser. The pulse duration of the ruby laser (2o nsec) is short compared to the CO_2-laser pulse. In fig.9 interferograms are shown taken at different moments. A fringe shift to the left corresponds to a refractive index < 1; this indicates electrons. A fringe shift to the right corresponds to a refractive index > 1, this indicates neutral gas.

In fig.9 only in the second interferogram a small fringe shift to the left can be seen. The electron density is too small to be calculated exactly. However, an upper limit for the electron density and the total number of electrons in the plasma can be estimated from the interferogram. The observed fringe shift is certainly less than 1/1o of fringe distance at 1 mm distance from the target. The thickness of the target, which is 1 mm, can be used as a scale. Assuming transverse dimensions of the plasma at this point to be 1 mm, we calculate the electron density $n_e < 3 \cdot 1o^{17}$ cm^{-3}. The upper limit for the total number of electrons can be estimated with the assumptions that the plasma flows continously from the target surface.

$$N_e = n_e \cdot v_p \cdot F \cdot \Delta\tau < 4 \cdot 1o^{16} \tag{1}$$

The plasma velocity v_p was determined with probe measurements to be $1.3 \cdot 1o^{7}$ cm/s. For the area F, a value $1o^{-2}$ cm^2 was used. The duration of the plasma flow $\Delta\tau$ is comparable to the time the laser beam takes to burn through the target, which was measured to be $1o^{-6}$ sec.

In the interferograms photographed near the end of the CO_2-laser pulse a fringe shift to the right due neutral gas can be seen. This flow of neutral gas from both sides of the target can be observed more clearly with shadowgrams.

From the shadowgrams (fig.1o) the velocity of the expanding neutral gas can be determined to be $v_F = 1.o \cdot 1o^5$ cm/s. This is low compared to the expansion velocity of the plasma. The reason for the flow of cold neutral gas can be easily understood. During the impact of the laser radiation, a small amount of hot plasma is produced, the rest of the target is heated either by contact with the plasma or by the compression wave leaving the focal area. After the laser pulse, the solid hydrogen disc disappears completely.

The energy transferred to the cold neutral gas cloud can be estimated from its velocity. The expansion starts after the disc of hydrogen has acquired internal energy in a time short compared to the expansion time. The velocity of the gas cloud can be identified as a one-dimensional rarefaction wave into vacuum. The kinetic energy is then given by /28/

$$E_{kin} = \frac{\gamma-1}{2\gamma} \cdot \frac{M}{2} \cdot v_F^2 \qquad (2)$$

The mass of the hydrogen disc M of 1 mm radius and 1 mm thickness is $2.o \cdot 1o^{-4}$ g. Considering that the rotations and vibrations of the hydrogen molecules are frozen we use $\gamma = 5/3$.
We then obtain

$$E_{kin} = o.o2 \text{ Joule}$$

In the following section we calculate the energy balance using this result and including the sublimation energy of the frozen hydrogen target.

Electrostatic probes measured the expansion of the plasma at different distances from the target and at different angles to the incident CO_2-laser beam. The probes, biased to - 3o V, detect only ions. The angles to the laser beam were 29 °, 45 ° and 67 °. Signals of several volts were measured by the 29 ° probe (fig.11). In the 45 ° direction the signals were 1/4 - 1/2 of the 29 ° probes. The signals from the 67 ° probe were decreased to 1/1o - 1/2o of the 29 ° probes. The expansion velocity of $V_p = 1.3 \cdot 1o^7$ cm/s is independent of the angle and distance of the probes. The total number of expanding ions was calculated from the probe measurements to be $o.2 \cdot 1o^{16}$ ions.

An interesting observation is shown in fig.12. The incident laser beam was detected in alternating shots with and without a hydrogen target. The signals are very reproducible. The results could be explained in the following manner. After the initial sharp peak and during the slower decay of the laser pulse, a strong reflection occurs in the presence of a target. Part of the reflected radiation enters the CO_2-laser and will be amplified. The bump in the laser output signal is a manifestation of this amplification mechanism. In the absence of the target, no reflection takes place. Consequently there is no amplification and the decay of the laser pulse continues smoothly. The reason for the reflection at the target is not clear.

IV. Comparison of Experiments with Theory

To visualize the physics of the experiment, we use a model of plasma production by laser which was developed in the past years by Caruso and Gratton /2o/ and Mulser and Witkowski /21, 22/. Roughly, the model assumes an absorption of the laser radiation in a thin sheet near the surface of the target. A hot plasma is produced and expands towards the laser into the vacuum. As a consequence of momentum conservation a compression or shock wave moves into the solid. The properties of the plasma, so created, and of the shock wave, are determined by the power density in the focus and the wavelength of the laser radiation.

The model is confirmed, qualitatively, by the observations. In the early period of the laser pulse the solid hydrogen is transparent to the lo.6 μ radiation, as can be seen in the transmission measurements. As the intensity rises the hydrogen is ionized and the radiation is absorbed strongly. Luminous plasma flow from the target into vacuum towards the laser; this can be observed in the streak photographs. Also there is evidence for the existence of the shock wave. As discussed in /2/ the "burn" velocity should correspond to the shock velocity. Soon after the arrivel of the shock wave at the rear face of the target, the target is expected to break up and become transparent to the laser radiation. This is indeed observed from comparison of absorption measurements and streak photographs.

For a quantitative comparison we use the formulas of /2o/ for the mean velocity V_p, the total number of particles N and the mean temperature T_p of the expanding plasma.

$$V_p = \text{const} \cdot r^{1/9} \cdot \lambda^{2/9} \cdot \phi^{2/9} \quad (3)$$

$$N = \text{const} \cdot r^{16/9} \cdot \lambda^{-4/9} \cdot \phi^{5/9} \cdot \Delta\tau \quad (4)$$

$$T_p = \text{const} \cdot r^{2/9} \cdot \lambda^{4/9} \cdot \phi^{4/9} \quad (5)$$

with

r = radius of focal spot
λ = wavelength of laser radiation
ϕ = power density in focal spot
$\Delta\tau$ = time duration of laser pulse

The velocity V_s of the shock wave in ionized hydrogen at a density corresponding to a solid is given by

$$V_s = \text{const} \cdot r^{-1/18} \cdot \lambda^{-1/9} \cdot \phi^{7/18} \quad (6)$$

In experiments with a ruby laser ($\phi = 10^{12}$ W/cm^2, 2r = 14o μ, $\Delta\tau$ = 18 nsec) good agreement was found between experimental and theoretical values using such a model /2/. We calculate the parameters of the CO_2-TEA-laser produced plasma using equations (3) - (6), and using the results of /2/ to calculate the constants used in equations (3) - (6) above.

The calculated numbers are compared with the measurements.

Table 1

	Ruby-Laser	CO_2-laser, theor.	CO_2-laser, exp.
v_p	$1.9\cdot 10^{7}$ cm/s	$1.0\cdot 10^{7}$ cm/s	$1.3\cdot 10^{7}$ cm/s ion probes
$N=N_i+N_o$	$4\cdot 10^{16}$	$0.74\cdot 10^{16}$	$N_e < 4\cdot 10^{16}$ interferom. $N_i = 0.2\cdot 10^{16}$ ion probes $N_o \approx 0.8\cdot 10^{16}$ energy balance
KT_p	~ 100 eV	5...15 eV	(10...25 eV)
v_s	$3.0\cdot 10^{6}$ cm/s	$3.1\cdot 10^{5}$ cm/s	$1.1\cdot 10^{5}$ cm/s transm. laser

The following factors were used

$$\Delta\tau_{CO_2}/\Delta\tau_R = 14.7$$

$$\lambda_{CO_2}/\lambda_R = 13$$

$$\phi_{CO_2}/\phi_R = 5.0\cdot 10^{-3} \qquad (9)$$

$$r_{CO_2}/r_R = 0.8$$

The ion probes are not able to detect neutral atoms and molecules. If the ions produced in the focus undergo partial recombination during expansion, the probes measure fewer ions than the number of ions N originally produced at the target. It was shown theoretically by Mattioli /23/ that in an expanding plasma strong recombination can take place. Also a good indication for such processes is given by the shape of the measured signals of the ion probes (fig.11). Seka, Schwob and Breton /24/ got similar results using a neodymium laser. They observed an ionized sheet of plasma followed by a flow of partially or completely recombined plasma. Therefore we assume that the expanding plasma is recombined partially.

For the determination of the number of recombined atoms we set up an approximate energy balance. When it becomes transparent the plasma has absorbed about o.25 Joules of energy up to that time. The energy of the expanding ions can be calculated from the probe measurements. We get o.o3 Joules. The energy of the cold matter flowing out of the rear of the target is o.11 Joules including vaporisation energy of o.o9 Joules. About one half of the absorbed energy is still missing. We assume that this energy is hidden in the expanding recombined gas, neglecting other processes like reflection of the laser radiation, emission of radiation from the target. Using this remaining energy of o.11 Joules and the assumption that the atoms flow with the velocity of the ions, we are able to determine the number of recombined atoms N_o

$$N_o \approx 0.8 \cdot 10^{16}$$

The total number of particles N is given by the sum of the number of ions N_i measured with probes and the numberof neutrals N_o estimated from energy balance. The result

$$N_{exp} = N_i + N_o = 1.0 \cdot 10^{16}$$

agrees well with the theoretical value of $0.74 \cdot 10^{16}$.

Direct measurements of the temperature were not made. But it is known that a constant ratio exists between the maximum of the plasma temperature T_p and the kinetic energy E_{kin} of the expanding ions. This was shown theoretically in /2o, 22, 25/. The constant itself depends on the model used. The temperature estimated in this way is written in brackets in the table.

A difference of a factor of 3 can be seen for the velocity of the shock wave. The reason for this seems to be that all the necessary assumptions in the theory of the shock wave are not fulfilled by the experimental situation. The theory considers a strong shock. In the experiment we get only a weak shock with a Mach number of about 1.

Conclusion

The production of a hydrogen plasma by a CO_2-TEA-laser can be described by the theory which was developed for Ruby and Neodymium lasers in the visible and near ir spectral range. The agreement between the theory and the experiment is good if we consider recombination, which is not included in the theory.

The experiments described are of great interest because with the development of more powerful CO_2-lasers, plasma production by 1o.6 μ radiation should become an important tool for plasma physics.

Acknowledgment

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TEA-CO_2-LASER

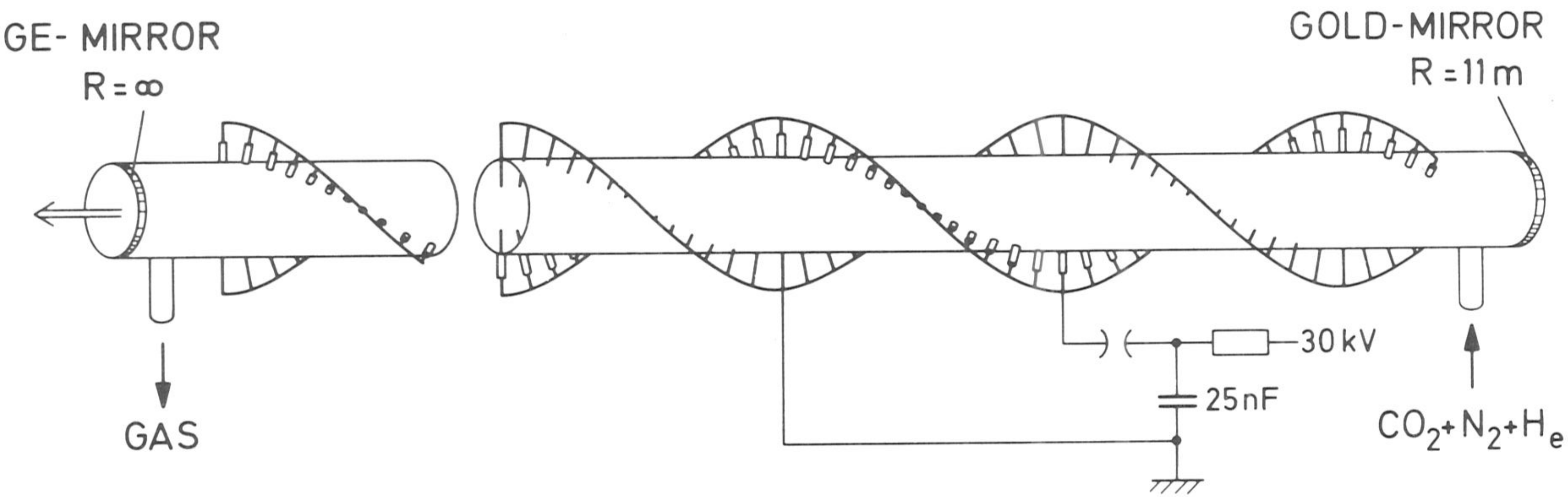


Fig.1   Principle of TEA-laser

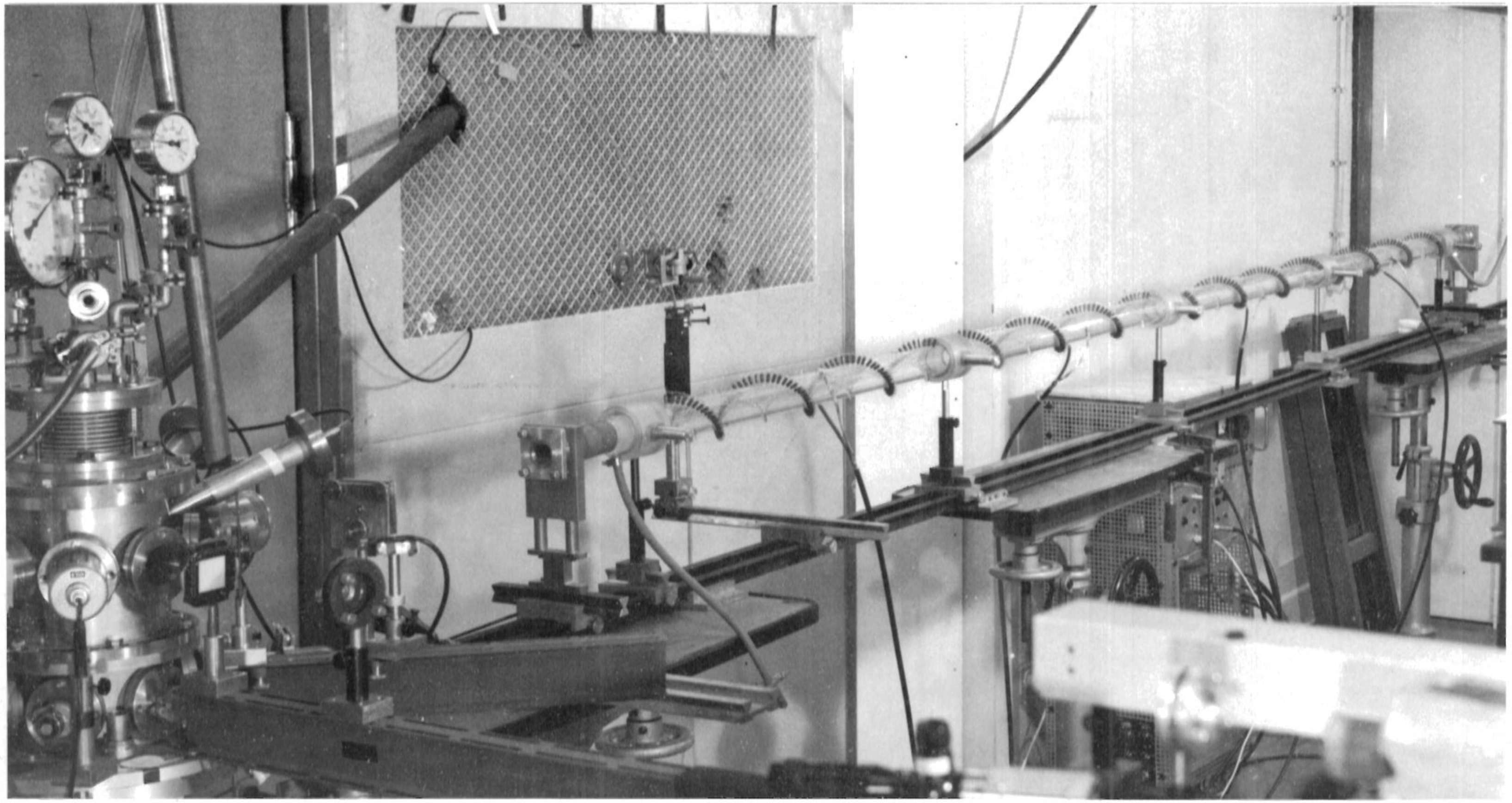


Fig.2 Photograph of TEA-laser and vacuum cell

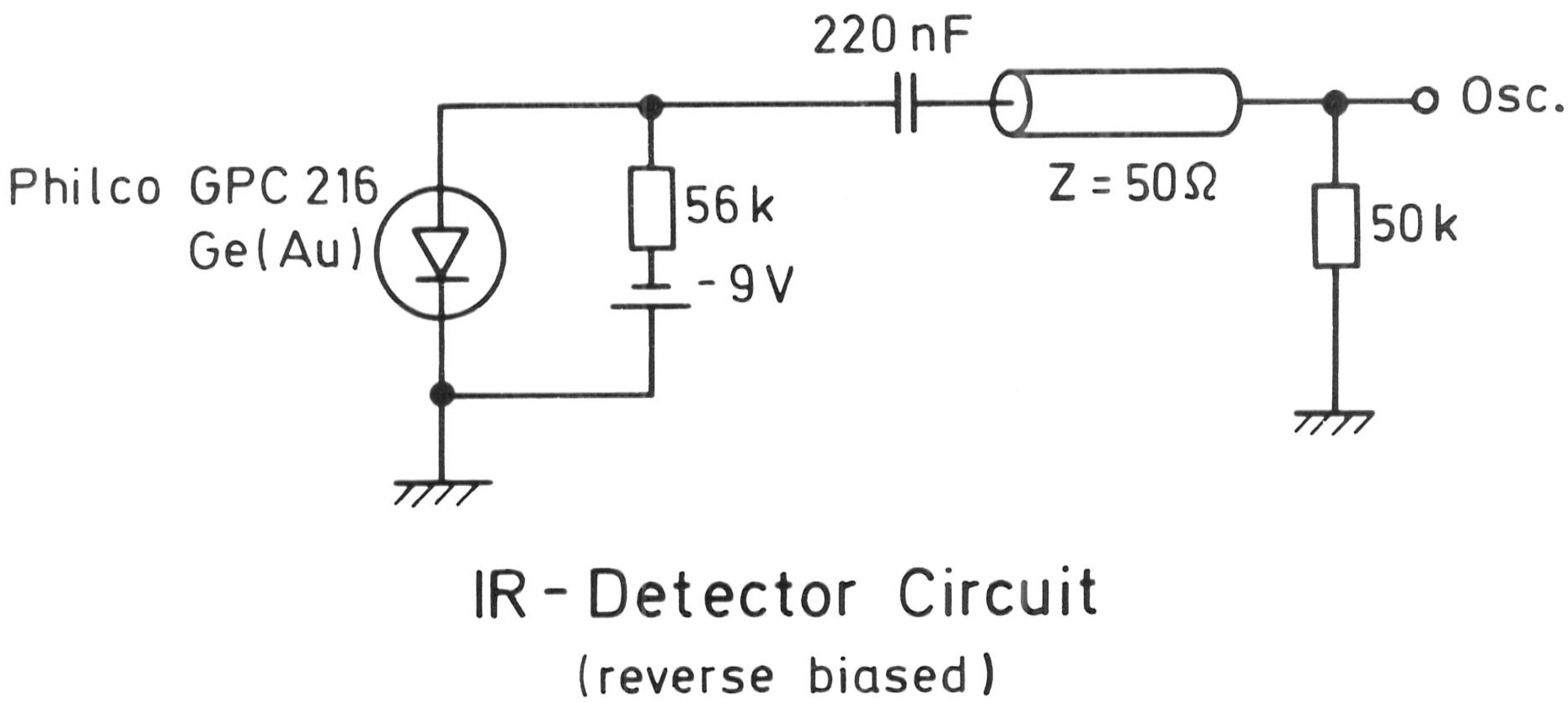


Fig.3 IR detector circuit

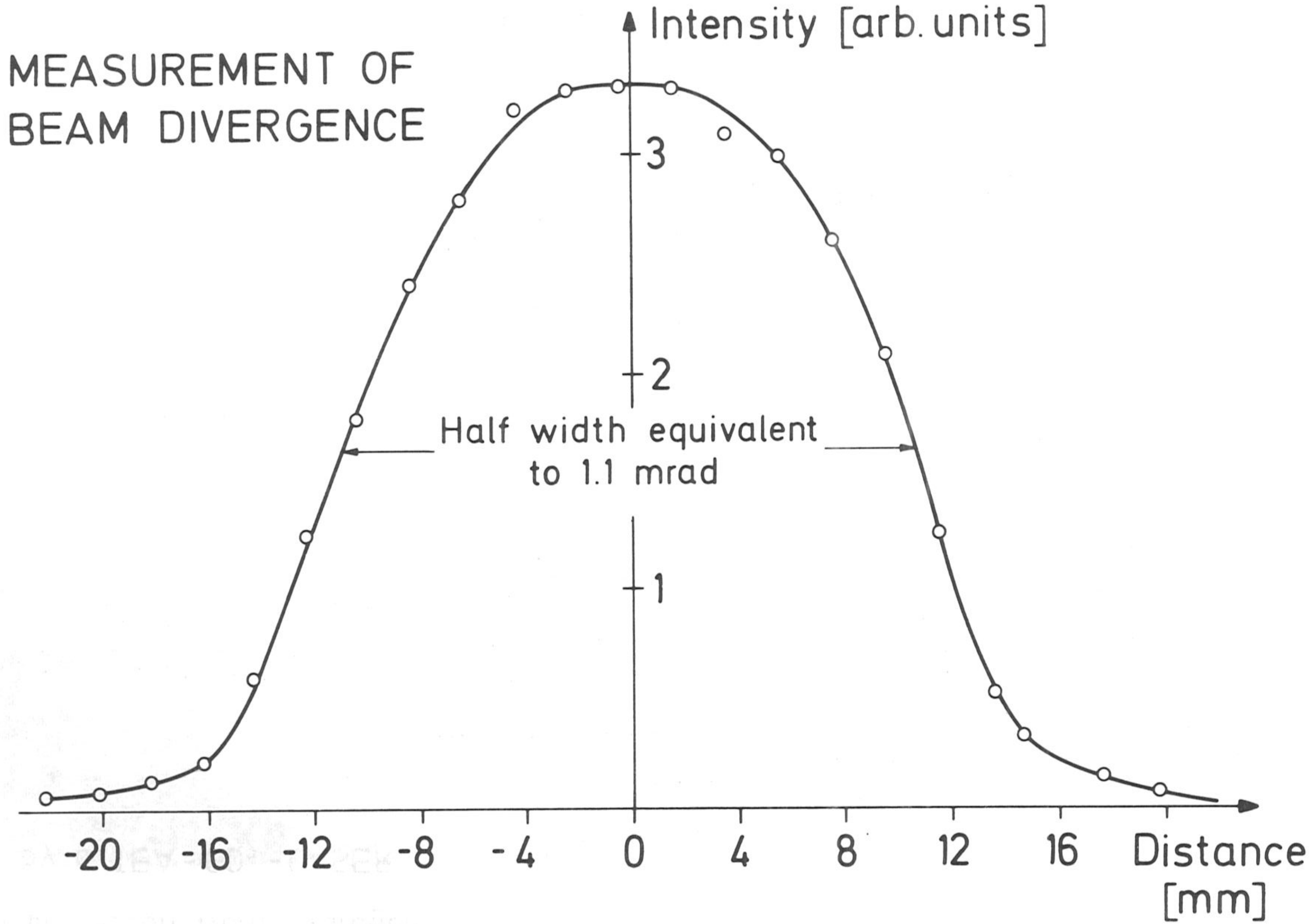


Fig.4 Beam divergence of TEA-laser

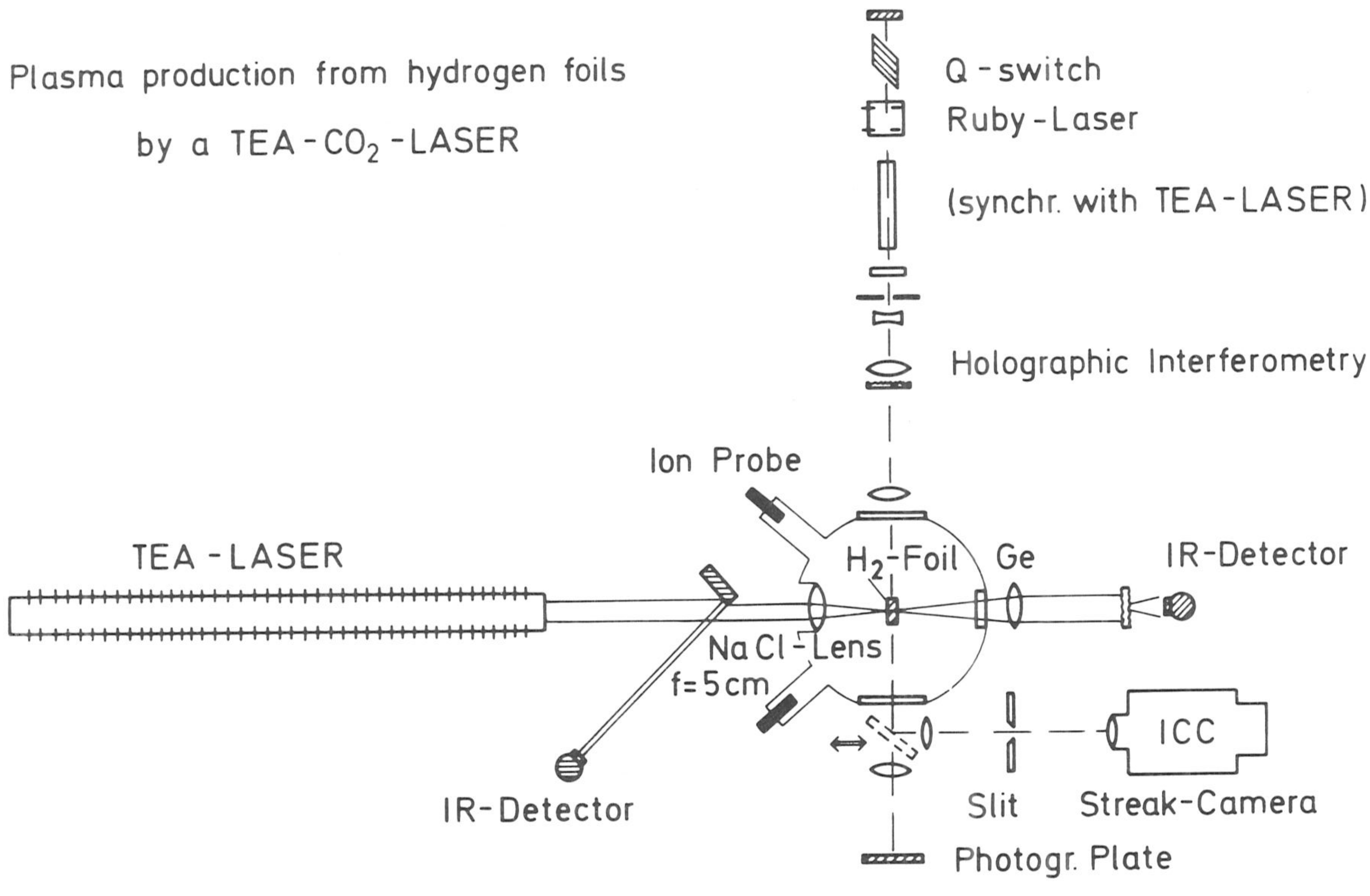


Fig.5 Experimental set-up

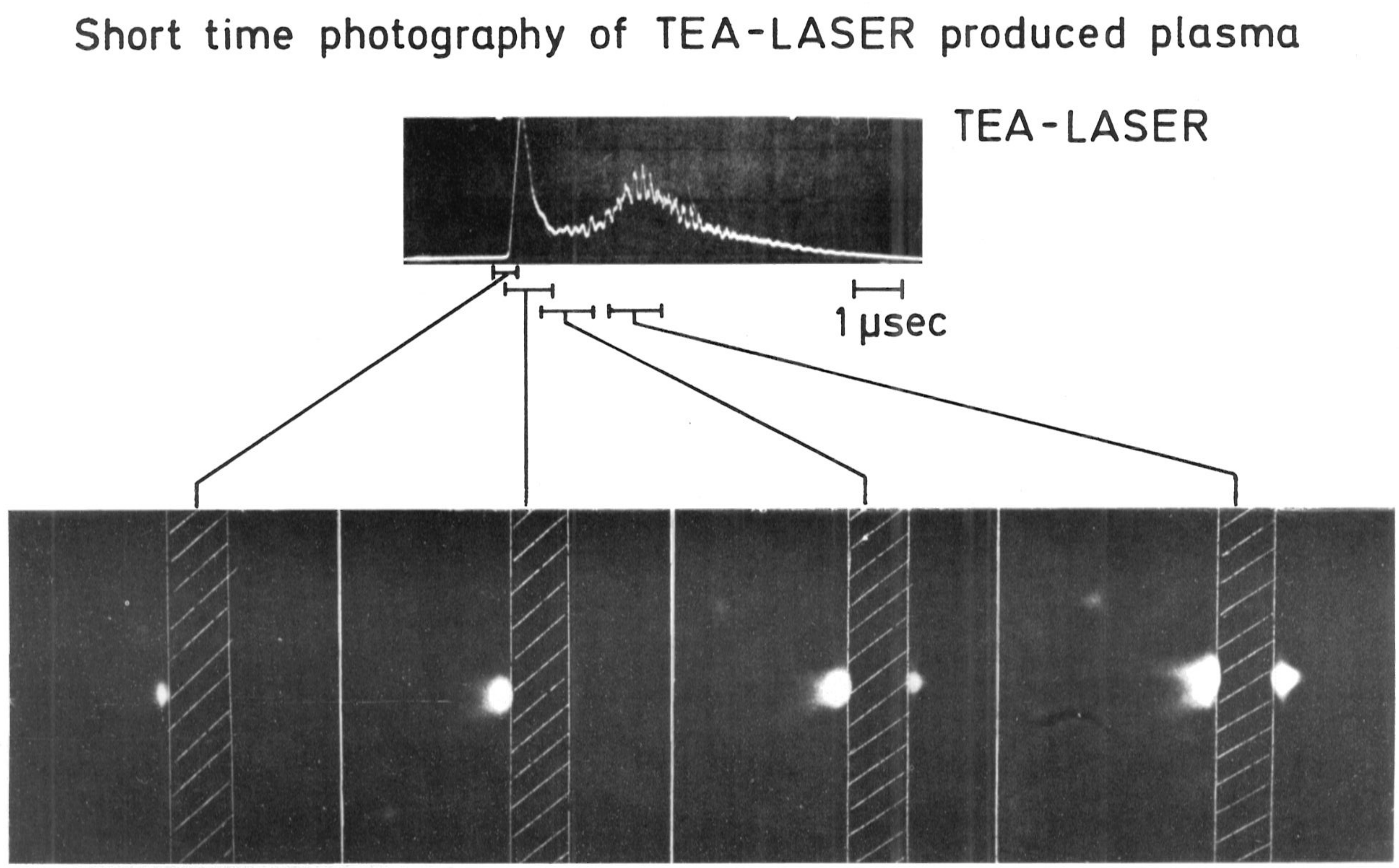
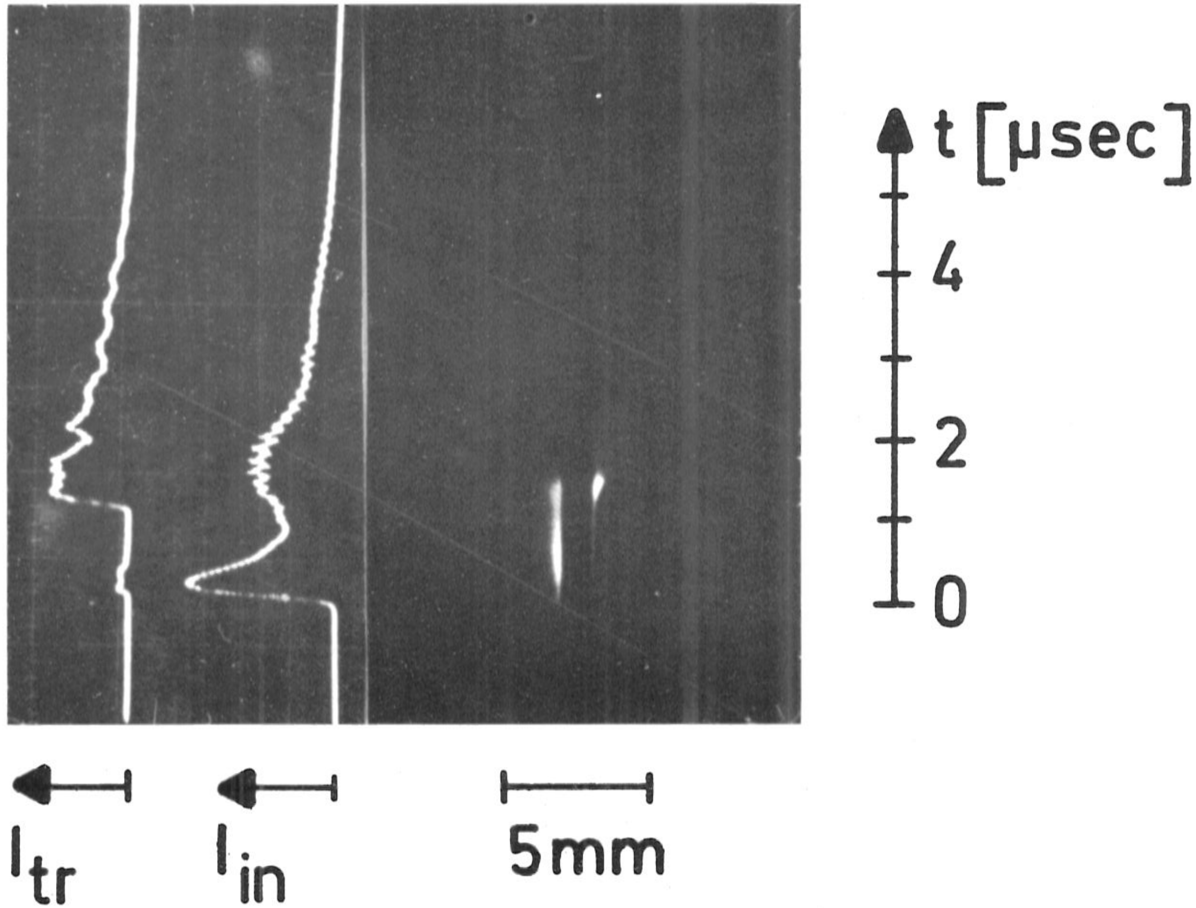


Fig.6 Short time photographs of TEA-laser produced plasma

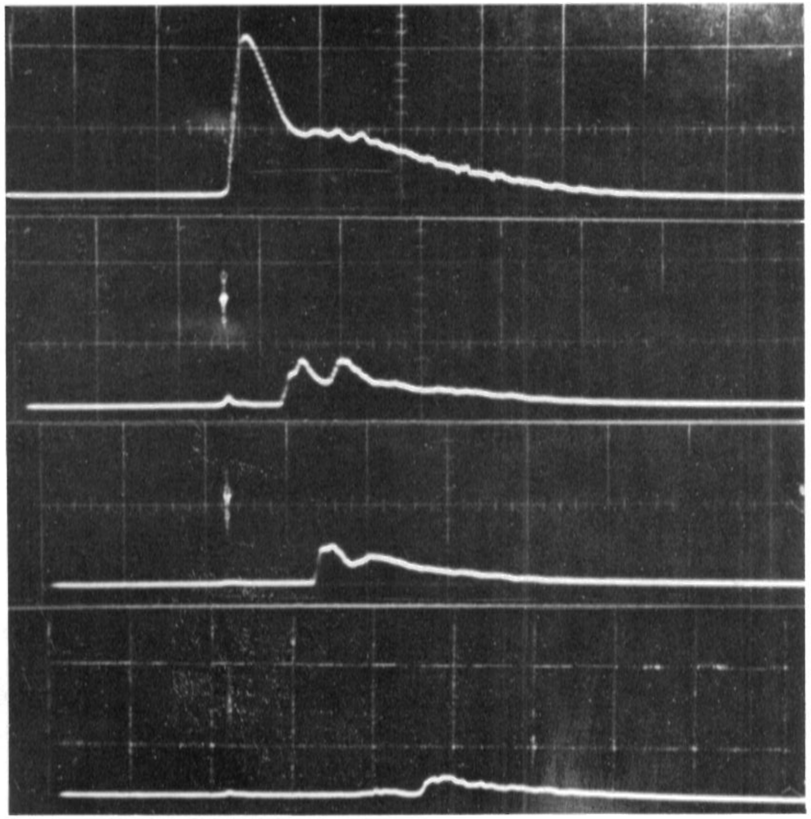
Streakphoto of Plasmaproduction on solid hydrogen by a TEA-LASER



I_{in} : incident 10.6 μ ; I_{tr} : transmitted 10.6 μ

Fig.7 Streak photography

Transmission of CO_2-LASER Radiation through foils of solid hydrogen



incident light

transmitted light

↓ increasing thickness of foils

1 µs/div

Fig.8 Transmission of laser radiation through H_2-targets

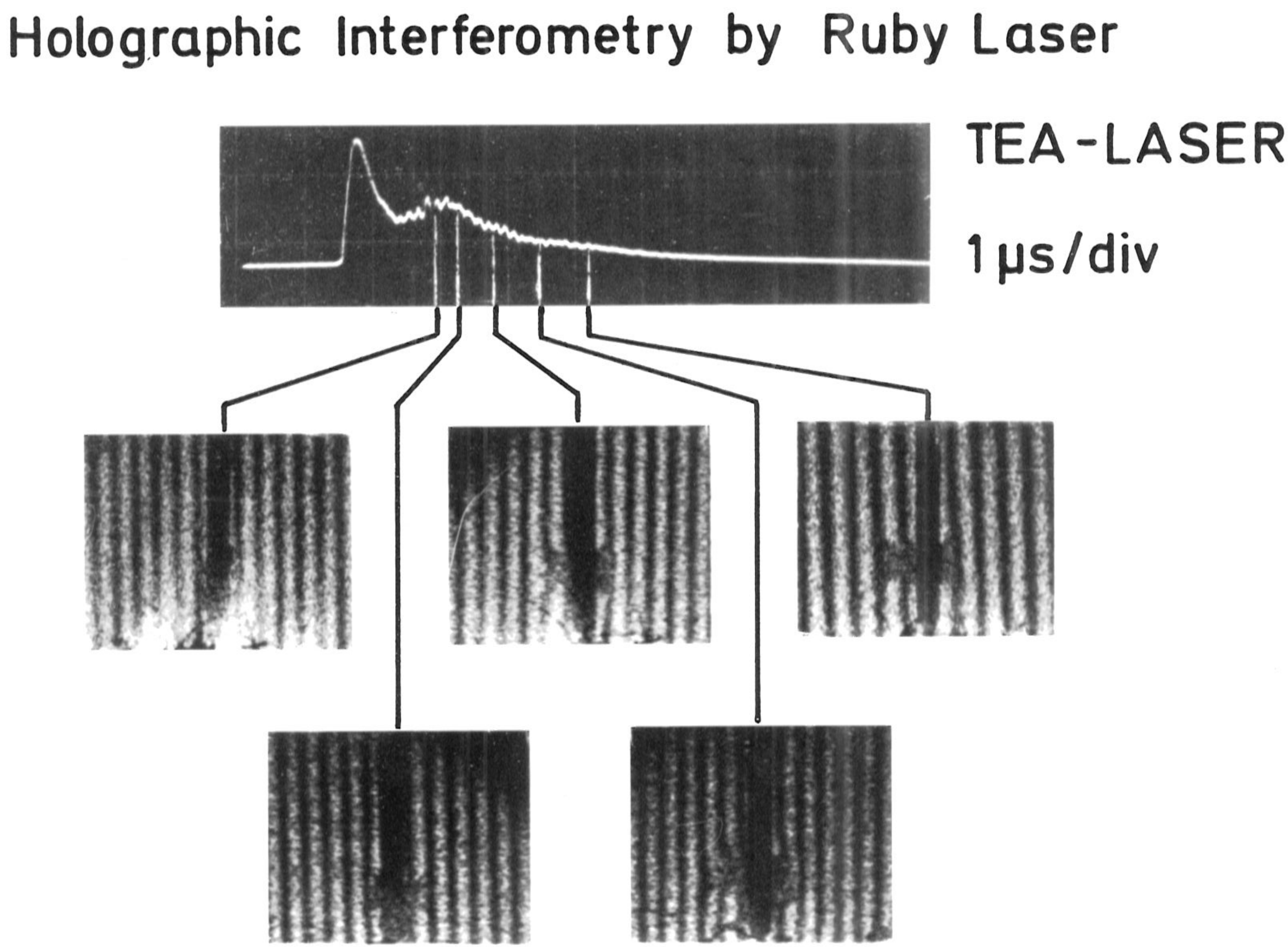


Fig.9 Holographic interferometry with Ruby laser

Plasma production by TEA-LASER from solid hydrogen

Shadowgrams by a synchronized Ruby-Laser

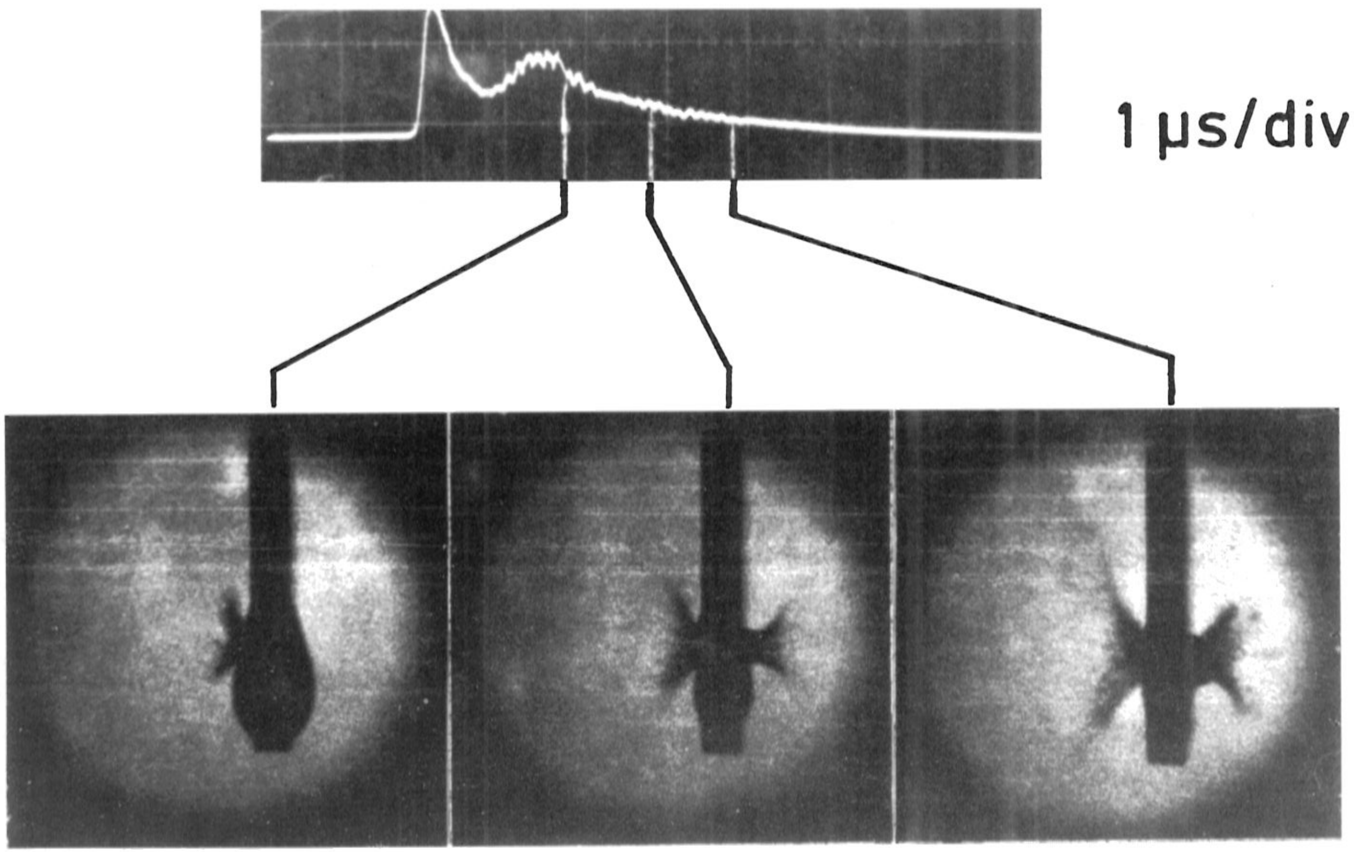
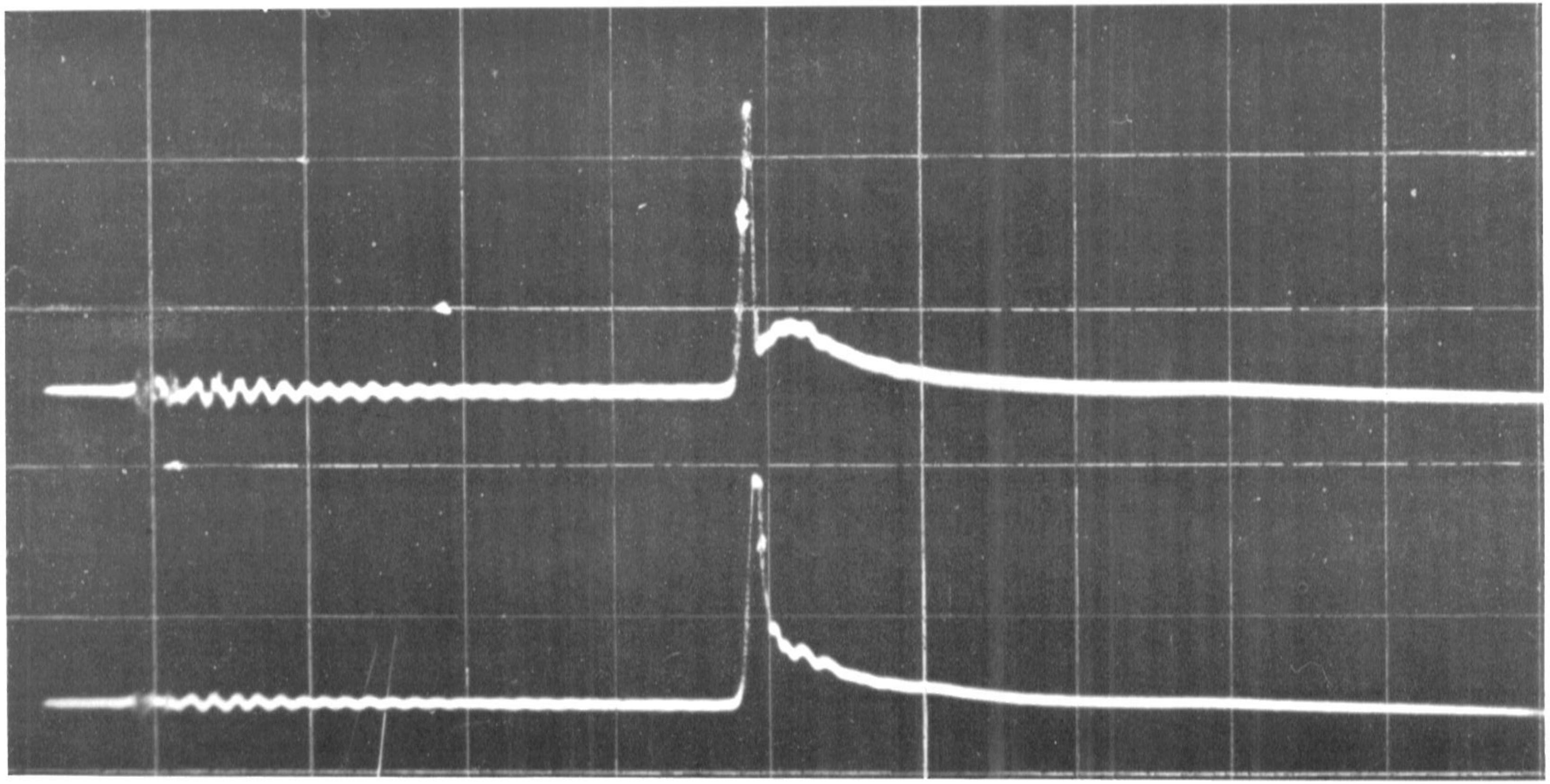


Fig.1o Shadowgrams



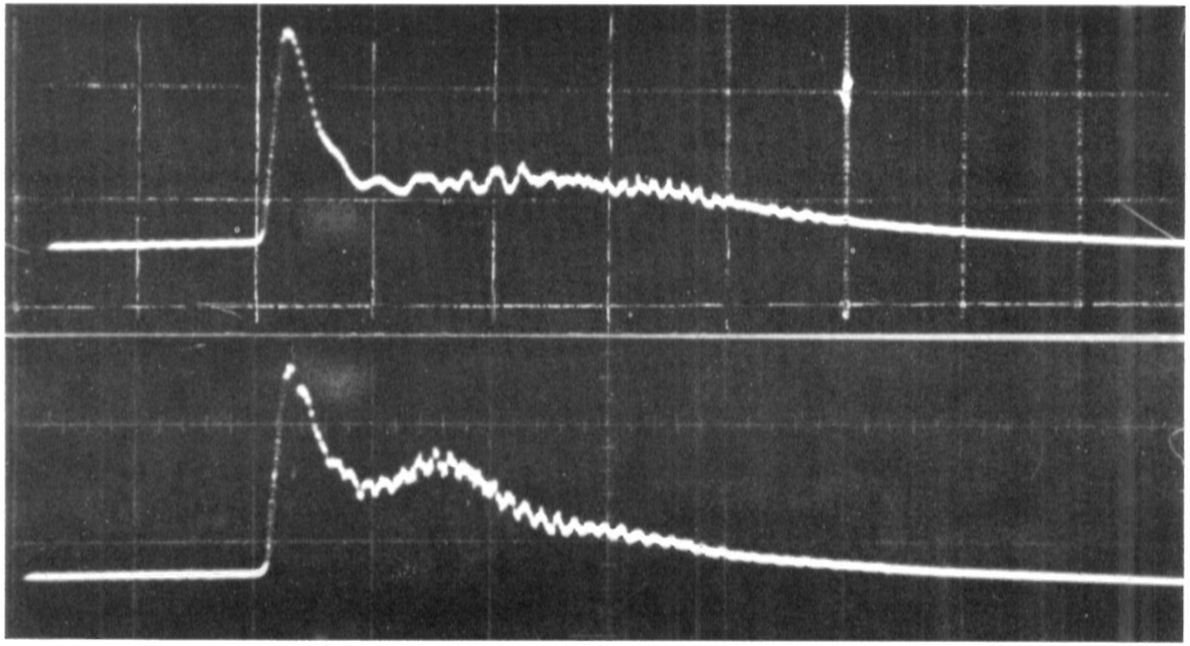
Electrical probes 1 μs/div

Hydrogen Plasma produced by TEA-LASER

Fig.11 Signals from electrostatic probes

Incident LASER - Radiation

(TEA - CO_2 - LASER)



without H_2 - Target

with H_2 - Target

1 µs/div

Fig.12 Reflection of laser radiation