CLM - R 154

CLM - R 154

UKAEA RESEARCH GROUP

Report

HOLOGRAPHY OF A CO_2 LASER GENERATED PLASMA

A C H ELKERBOUT
J W VAN DIJK
T P DONALDSON

CULHAM LABORATORY
Abingdon Oxfordshire
1976
Available from H. M. Stationery Office

C/18

£1.00

UDC: 535.41:533.9.03:621.375.826

CLM-R 154

HOLOGRAPHY OF A CO_2 LASER GENERATED PLASMA

A.C.H. Elkerbout[+], J.W. Van Dijk[+], T.P. Donaldson[*]

Culham Laboratory, Abingdon, Oxon, OX14 3DB, UK
(Euratom/UKAEA Fusion Association)

ABSTRACT

An experimental technique for generating holographic interferograms is discussed and illustrated with results obtained on a plasma generated by a 75 J CO_2 laser pulse incident at intensities of $\sim 9 \times 10^{12}$ W/cm^2 on a plane carbon target.

[+] R.K. Hogere Teknische School, Netherlands

[*] Queen's University, Belfast

December 1975

SBN: 85311 043 3

1. INTRODUCTION

The CO_2 laser used to produce the plasma was a double-discharge transversely excited system generating a 75 J pulse in 50 nsecs(1). This was focused onto a plane carbon target with a 30 cm focal length spherical mirror. The measured focal diameter was 150 microns, giving an incident intensity of 9×10^{12} watts cm^{-2} on the target. The electron density of the plasma produced was measured using the holographic technique discussed in this report.

If two holograms made of a phase object are superimposed(2,3), where one of the holograms differs slightly from the other because of the introduction of a refractive index change, Moire beats will be produced which are exactly equivalent to the interference fringes produced by a conventional Mach Zehnder interferometer, when the same phase object is placed in one of its arms. The Moire fringes are formed by the very fine interference patterns that make up the holograms. A great advantage of holographic interferometry is that the quality of the Moire fringes is independent of the quality of the holograms and thus (to a certain degree) of the quality of the mirrors and windows of the holographic system. A consequence of this is that relatively inexpensive optics can be used. Two very important requirements remain however: the spatial coherence of the laser used for making the holograms must be such that very fine high order fringes can be produced and a detector must be used to record the holograms (in this case a photographic plate) which is capable of resolving these very fine fringes. The particular form of holographic interferometry used here is called "double beam fractional fringe holographic interferometry".(4)

The laser beam is first split into two by a 50% beam splitter (figure 1); the beam traversing the test section (ie the plasma) is known as the scene beam and the other the reference beam. When these two beams are recombined on the holographic plate a hologram of the test section is formed. A first exposure, the reference exposure, is made with no plasma present. Then a second exposure is made with plasma in the test section. The refractive index change, introduced by the insertion of the plasma, causes the second exposure to experience phase differences relative to the reference exposure and Moire fringes are formed. Interpretation is facilitated by the introduction of a background wedge-fringe pattern created by a suitable change in path length in either the reference or scene beam between exposures. This background pattern makes it possible to measure fractional fringe shifts (~ $\lambda/10$), thus greatly improving the accuracy of the technique.

If the plasma under investigation is fully ionised the refractive index is dominated by the electron refractivity. The fringe displacement, p, due to the substitution of plasma for vacuum, is:

$$p = \int_0^L (\mu - 1) \frac{d\ell}{\lambda}$$

where μ is the electron refractivity, $d\ell$ is the element of path length along the line of sight, L is the plasma length, λ is the wavelength of the laser radiation. Substituting the value of μ, it follows(5) that for $\lambda = 6943$ Å, $\int n_e d\ell = 3.7 \times 10^{17}$ p, where n_e is the electron density in electrons cm^{-3}. To determine the density at a given point one tests for cylindrical symmetry and, if azimuthal variations are negligible, performs an Abel inversion(6). In the present work fringe shifts are recorded at 21 radial positions (Fig. 2) and used as input to the Abel inversion code.

2. APPARATUS

A 50% dielectric beam splitter splits the beam into the reference and scene beams (Fig. 1). The scene beam traverses the plasma interaction chamber vertically. Because the path lengths of the scene and reference beams have to be matched to within the coherence length of the ruby laser an adjustable delay line made of 4 mirrors is placed in the reference beam. The first mirror of the delay line also serves as the background (wedge-fringe) mirror.

After the reference shot is made a current of 2 amps is passed through a NiCr wire which is part of the background fringe mirror mount (Fig. 3). This causes the wire to expand so that the mirror tilts through a very small angle. The tilting introduces a small, controlled, change in path length in the reference beam and a straight background fringe pattern is formed at the hologram. Both the reference and scene beam pass through imaging lenses and 6943 Å interference filters to discriminate against plasma light; the hologram is recorded on Agfa 10E75 plates. This system was also used for shadowgraphy, a technique in which a collimated light beam passes through the test section and gives information about the shape and size of the object under study.

The diagnostic laser is a Korad K1500, having a φ 10 x 100 mm ruby oscillator crystal. One side of the oscillator is terminated with a 99.9% reflecting dielectric mirror and the other side with a 26% reflecting, two plate, temperature controlled, sapphire resonant reflector (etalon). The laser pulse is clipped, using an electro-optic switch and laser triggered spark gap, and sharpened using a Q-switching dye solution in a quartz cell.

In order for the ruby laser to act as a high Q optical resonator the etalon and output mirror have to be parallel to within 3 seconds of arc. This can be achieved by diverting the beam of a 1 mW CW HeNe laser into the oscillator using a 90° prism. To align the oscillator it is of paramount importance that the HeNe beam is inserted into the system exactly along its optic axis, by passing the beam through two perspex blocks having apertures exactly on the optic axis. The HeNe beam, resonant-reflector reflections and back mirror reflections are superimposed until interference fringes are observed near the output mirror of the HeNe so that the oscillator will meet a 3 seconds of arc criterion for parallelism and will stay aligned for periods extending from half a day to many weeks.

The path lengths of the scene and reference beams are matched by using a piece of string to measure their lengths and adjusting the delay line accordingly. A HeNe laser is used to adjust the system and the reference and scene beam are made to overlap each other exactly at the holographic plate.

The following sequence of tests were made:

(a) A Kodak 649F plate was mounted in the camera and the ruby fired. A current of 2 amps was now passed through the NiCr wire and a reference shot taken. This test produced holograms which showed a very low diffraction efficiency and had barely discernible fringes. The reason for this was thought to be either a lack of temporal or spatial coherence or a combination of both.

(b) In order to improve the temporal coherence it was decided to tune the optical delay line. To do this the path length of the reference beam was increased or decreased in steps of 1 cm. It was found that holograms could be produced within a path length change of 40 mm, thus indicating a coherence length of 40 mm. This was consistent with the theoretical coherence length for ruby light:

$$\ell_c = \frac{\lambda^2}{\Delta\lambda} = \frac{5 \times 10^7 \text{ Å}}{0.1} = 50 \text{ mm}.$$

However, even the holograms produced in the optimum position of the delay line had insufficient diffraction efficiency.

(c) The next step was to try to improve the spatial coherence. The best results are obtained if the laser operates in the TEMoo mode. To stimulate lasing in low order transverse modes a 3 mm pinhole was inserted inside the cavity and the oscillator pumped at near threshold voltages. This produced a low order mode structure. Holograms taken with this configuration showed a high diffraction efficiency indicating high spatial and temporal coherence. The fringes produced, however, were wavy and sometimes split (see figure 4(a)).

(d) To improve further the spatial coherence and uniformity of the beam a 10 X beam expander was put in the system. Holograms taken this way showed a very significant improvement, with strong diffraction and perfectly straight fringes of high order (see figure 4(b)).

(e) The imaging of the plasma plane was improved by using a 20 cm focal length lens to image 3:1 onto the holographic plate,and a similar compensating lens in the reference beam. This facilitated the interpretation of the fringe shifts relative to the target and plasma, since without this lens the target plane was not imaged clearly onto the holographic plate.

The following technique is used to process the holographic interferogram:

1. Provide heavy double exposure.
2. Develop in Kodak D19 developer for 5 minutes.
3. Rinse in running water for 30 seconds.
4. Fix for 90 seconds.
5. Rinse in running water for 2 minutes.
6. Bleach in chronium intensifier until plate is uniformly yellow (about 30 seconds), cf. Appendix 1.
7. Rinse for 1 minute in running water.
8. Rinse in clearing bath until yellow disappears (about 2 minutes), cf. Appendix 1.
9. Rinse in running water for about 10 minutes.
10. Dip in Kodak Photo-Flo for 30 seconds.
11. Allow to dry.

When the hologram is processed it is possible to reconstruct by making a contact print. A proper reconstruction process, however, is far superior to this since a hologram acts as a diffraction grating; by making a contact print one uses the zeroth order, but by using the first diffraction order the spurious noise patterns seen in the zeroth diffraction order are eliminated. A diagram of the reconstruction apparatus is shown in figure 5, where the condenser images the filament of a microscope lamp onto a slit, which selects the first order spectrum which is then imaged by a second lens onto a screen.

3. RESULTS AND CONCLUSIONS

Figure 6(a) shows a hologram taken at the centre of the laser-plasma interaction while 6(b) shows a holographic shadowgram. Fig. 7 shows the electron density profile calculated by Abel inversion from the first hologram. A maximum density of $n_e = 10^{19}/cm^3$ was observed while a steep density gradient can be seen near the centre of the laser pulse.

This method of holography was chosen because it gives a high resolution and can be reconstructed using incoherent light, compared with scatter plate holography, where the scene and reference beams are separated by a scatter plate(5). (Note that good holograms were obtained with this technique without using a holographic quality ruby - although with the scatter plate technique a holographic quality ruby would be necessary).

The resolving power of the system is not limited by the holographic optics, but by the lens used to image the plasma onto the photographic plate. If a microscope objective is used instead of a lens(7) then diffraction limited optics are attained (~ 5 µm spatial resolution).

The most critical requirement of the holographic system was found to be spatial coherence of the laser. Operation in TEMoo and exact superposition of the scene and reference beam on the holographic plate are both desirable.

When beam expansion was used the quality of the oscillator ruby was found to be less critical than it would be for conventional three dimensional holography. There was even some advantage in reducing the spatial coherence, to a point where fringe quality was not seriously impaired but wedge fringes from optical components were eliminated. This system has also been operated frequency doubled, to look at higher plasma electron densities with the higher frequencies thus available. With such frequency doubling or tripling techniques, multi-wavelength holographic density contours become possible, so that density gradients in the plasma can be measured to a very high degree of accuracy.

ACKNOWLEDGEMENTS

We wish to thank Dr P.D. Morgan for the use of an Abel inversion computer code.

References

1. Culham Laboratory Progress Report CLM-PR 15 (A15). (1974).
2. STROKE, G.W. An introduction to coherent optics and holography. Academic Press, New York, 1966.
3. LEITH, E.N. and UPATNIEKS, J. J. Opt. Soc. Am. 56, 923, 1966.
4. JAHODA, F.C. JEFFRIES, R.A. and SAWYER, G.A. Appl. Optics, 6, 1407, 1967.
5. JAHODA, F.C. and SIEMON, R.E. La-5058-MS-UC 37, October 1972.
6. BOCKASTEN, K., J. Opt. Soc. Am. 51, 943, 1961.
7. ATTWOOD, D.T. and COLEMAN, L.W. App. Phys. Lett. 24, 408, 1974.

APPENDIX I

Photographic Solutions

1. Bleaching Bath

Stock solution:

Quantity	
500 ml	Water
90 gr	Potassium dichromate
65 ml	Hydrochloric acid (concentrated)
1 litre	Water to make

For use take 1 part of stock solution and 6 parts of water.

2. Clearing Bath

500 ml	Water
15 gr	Sodium metabisulphite
1 litre	Water to make.

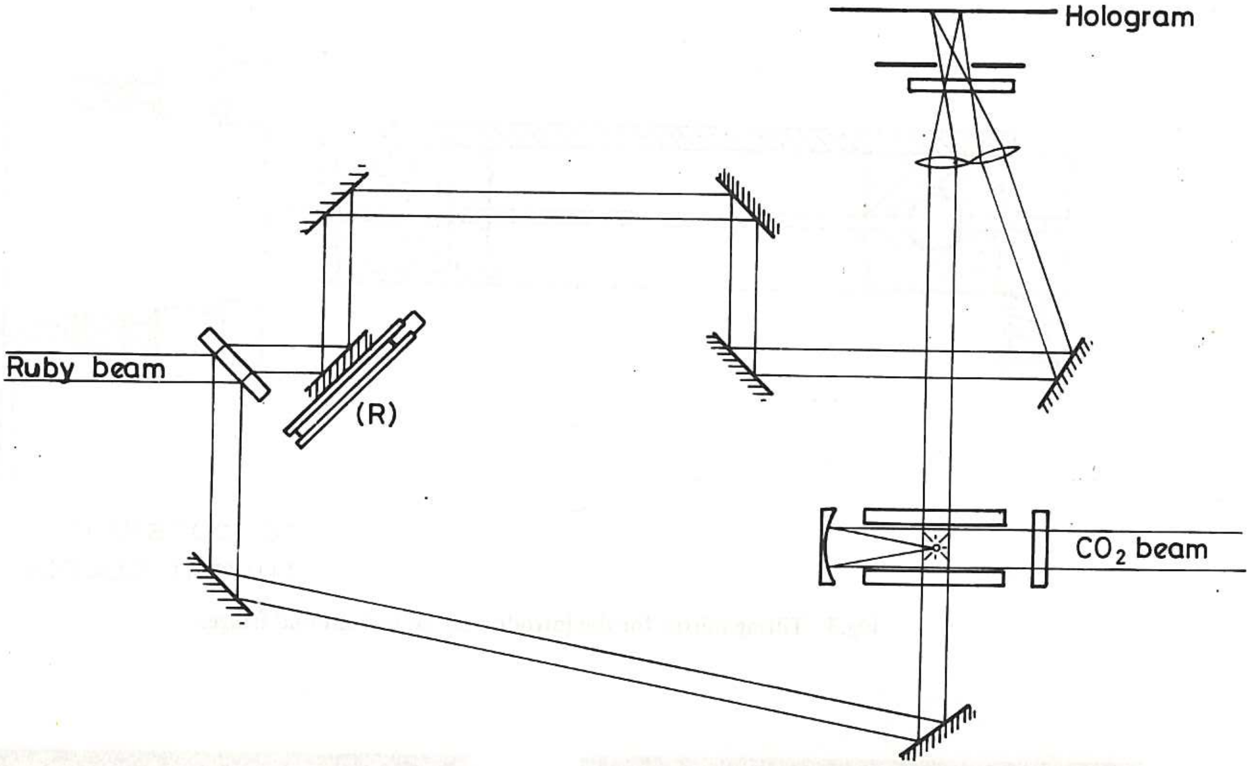


Fig.1 Holographic interferometer.

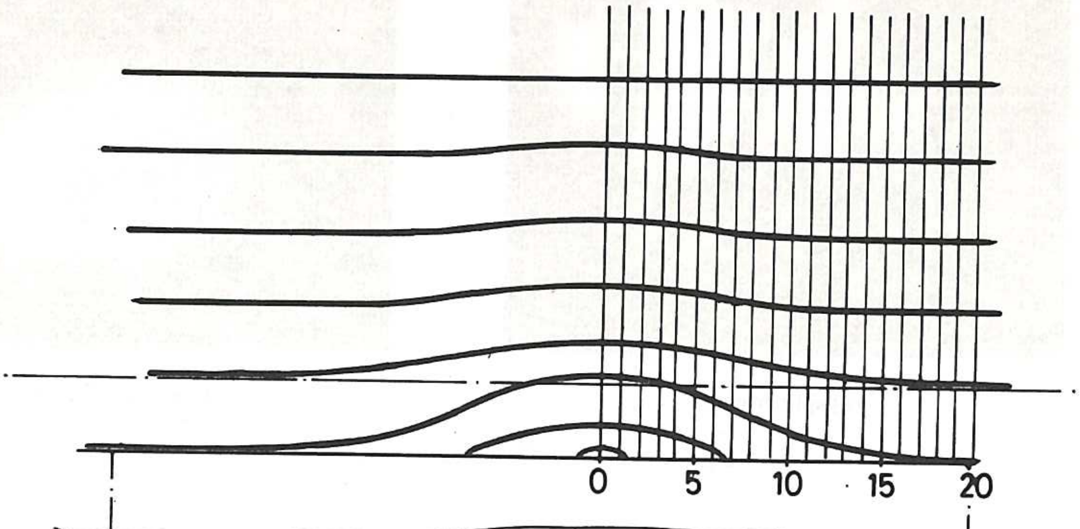


Fig.2 Analysis of holographic interferograms, where the fringe shifts are measured at the 21 radial positions indicated.

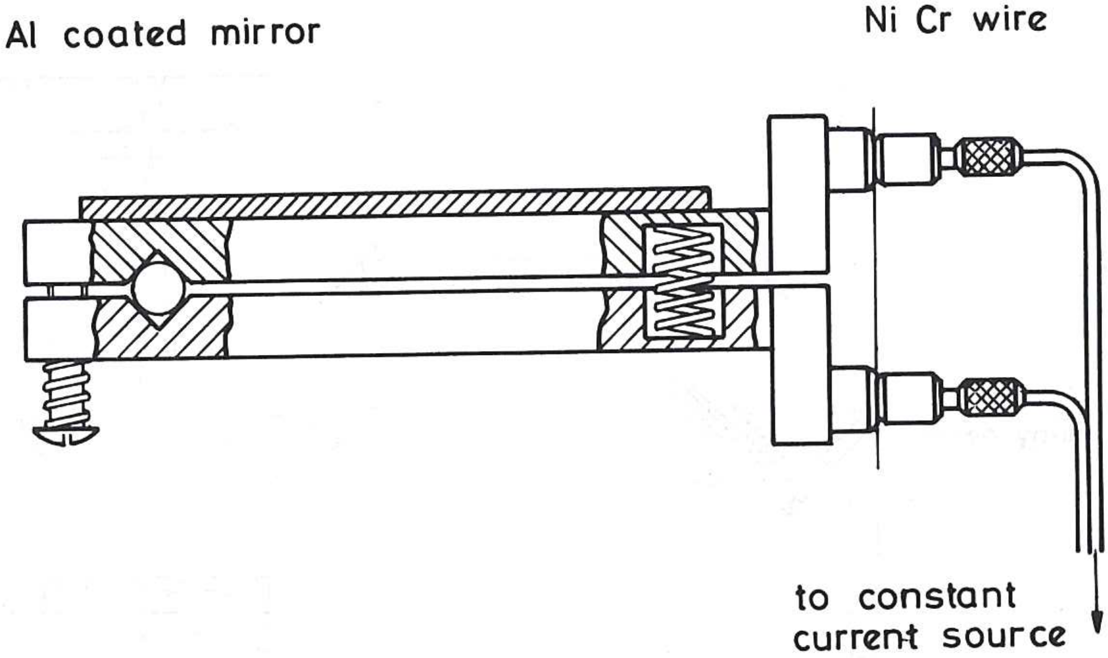
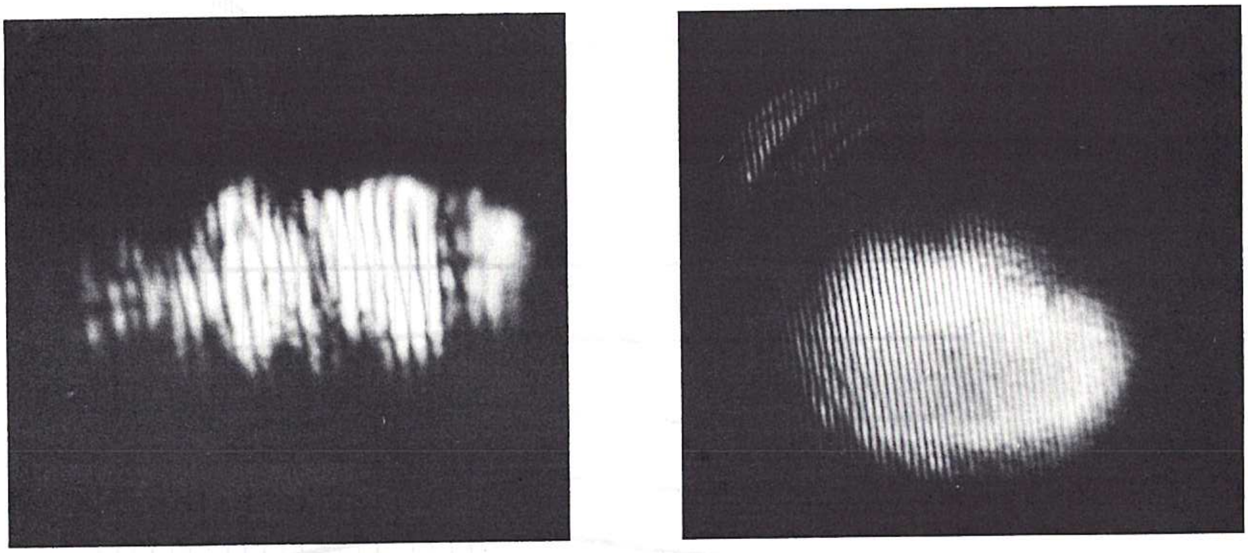


Fig.3 Tilting mirror for the introduction of background fringes.



(a) split fringes.

(b) straight fringes.

Fig.4 Examples of holographic interferograms showing

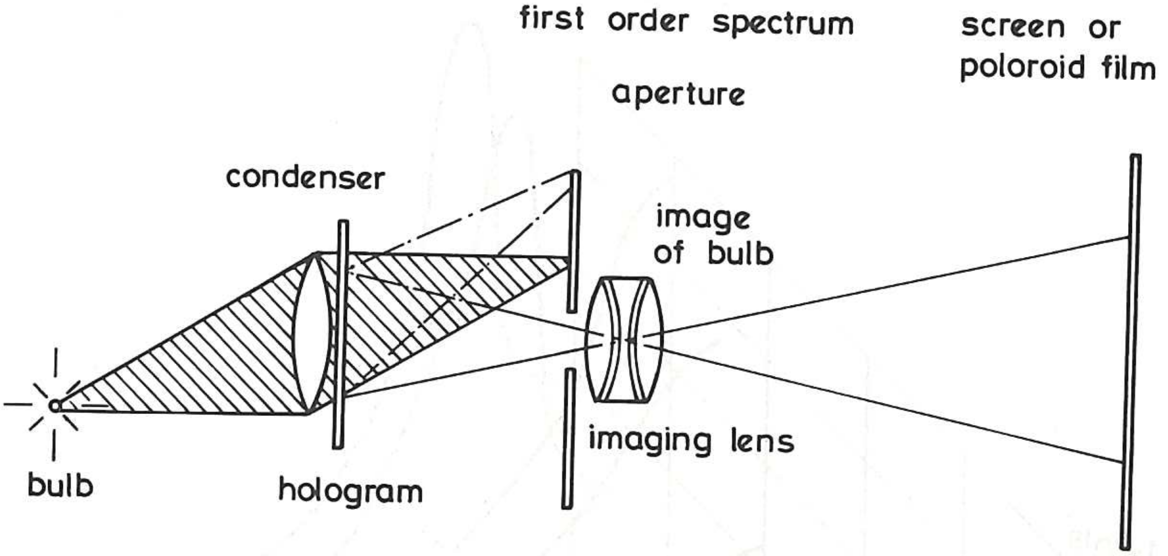


Fig.5 Hologram reconstruction.

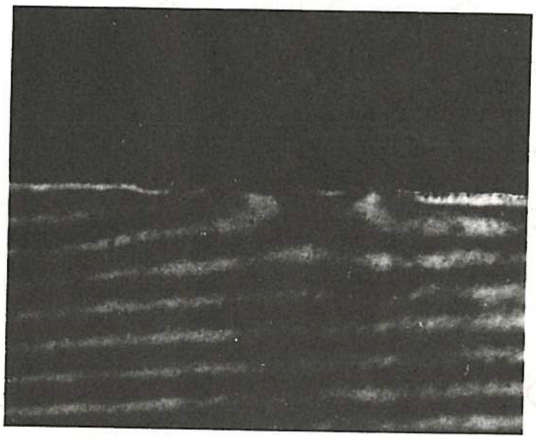


Fig.6(a) Holographic interferogram taken at t = 25 nsecs, (the centre of the CO_2 laser pulse)

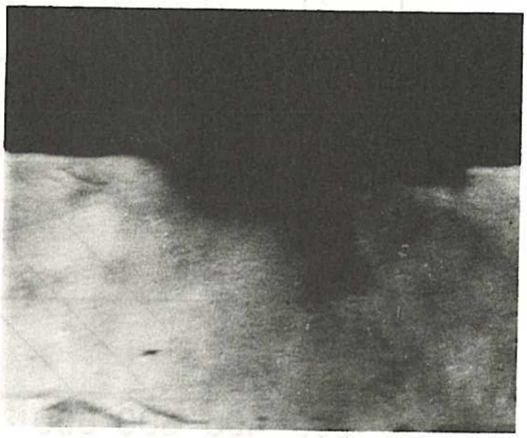


Fig.6(b) Holographic shadowgram taken at t = 25 nsecs.

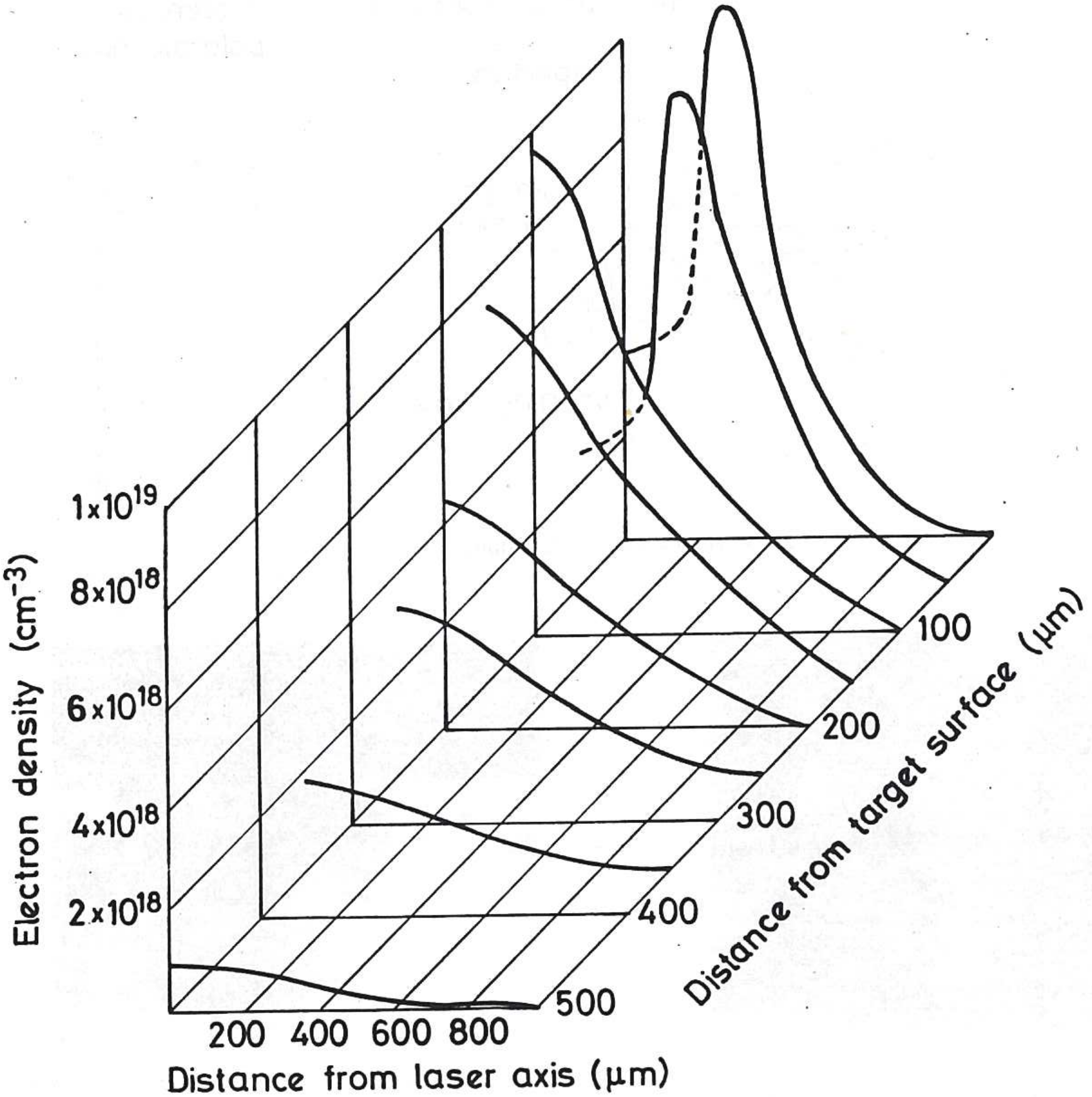


Fig.7 Radial electron density profiles obtained from the interferogram in 6(a).

HER MAJESTY'S STATIONERY OFFICE

Government Bookshops

49 High Holborn, London WC1V 6HB
13a Castle Street, Edinburgh EH2 3AR
41 The Hayes, Cardiff CF1 1JW
Brazennose Street, Manchester M60 8AS
Wine Street, Bristol BS1 2BQ
258 Broad Street, Birmingham B1 2HE
80 Chichester Street, Belfast BT1 4JY

Government publications are also available
through booksellers