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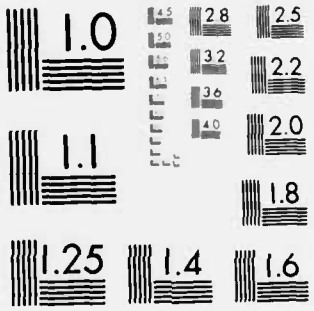

NRL Memorandum Report 5278

Optical Imaging of a Coupling Region Between Inter-Streaming Plasmas

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Recent studies in the NRL HANE simulation experiment have been directed toward a higher pressure/low altitude regime where HANE events (e.g., Checkmate) and early HANE simulations ($P \gtrsim .5$ Torr) had shown a turbulence or jetting. The main diagnostic was dual-time, dark-field shadowgraphy which had sufficient temporal (300 psec) and spatial (10 micron) resolution to resolve details of the developing structure. A well-defined, initially nearly-spherical front or coupling region is seen which slows down, indicating mass pick-up. At higher ambient pressure, lower laser energy and later time, the front shows a breakup. When conditions are just marginal for break-up, the front tends to form a single protuberance or aneurism which grows in time.

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OPTICAL IMAGING OF A COUPLING REGION BETWEEN INTER-STREAMING PLASMAS

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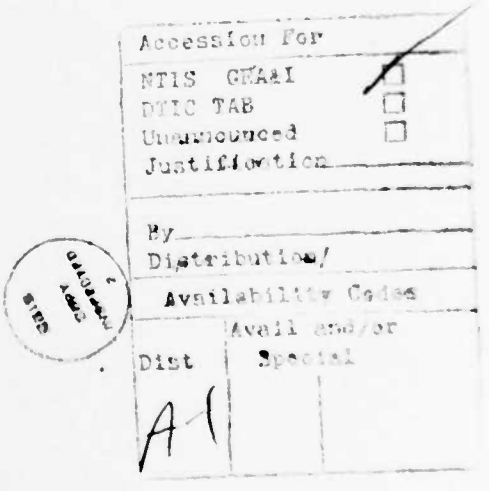

OPTICAL IMAGING OF A COUPLING REGION BETWEEN INTER-STREAMING PLASMAS

I. INTRODUCTION

Our studies at higher ambient pressures (> .2 Torr) were aimed at understanding phenomena in HANE events at altitudes of 100 to 200 km. For example, jetting and a turbulent appearing coupling region were seen in Checkmate. The original[1,2,3] NRL simulation experiment (~ 1970) had shown a turbulent appearing coupling region at higher ambient pressure (> .5 Torr) and helped to motivate the most recent (high-pressure) HANE studies. Our present (non-resonant) optical probing diagnostics are useful at these higher densities. We start with a brief review of the 1970 data.

Visualization of the coupling region between the expanding debris plasma and the ambient plasma has been an important objective of the HANE simulation experiments. This has been accomplished by either fast photography of the emitted light or by using a short-pulse probing laser beam. Fast framing photography in the 1970 NRL experiment showed a region of strong momentum coupling. Typically, 10 Joules of laser energy in a 30-45 nsec pulse was used to produce target debris (CH_2) which streamed into an ambient nitrogen gas at 0.1 to 1 Torr. The coupling region in the 1970 experiment was also imaged using second-harmonic shadowgraphy and was seen to develop a turbulent appearance at higher ($\gtrsim$ .5 Torr) pressure and at later times.

The time dependence of the coupling region is shown in Fig. 1 for an ambient nitrogen background gas at 200 mTorr. The coupling region was well formed by 53 nsec and was observed out to 92 nsec. These shadowgrams were taken in the second harmonic light (5320 Angstrom) of the main laser beam. Although the probe pulse was about 20 nsec in duration, a sweeping action gave an effective exposure of only a few nanoseconds.

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The pressure dependence of the coupling region is shown in Fig. 2. These shadowgrams were all taken at 92 nsec and show the dependence on the pressure of an ambient nitrogen gas. Above about 500 mTorr the coupling region shows a turbulent appearance. This is the phenomena which we want to investigate in the present experiment. The coupling region observed in the original experiment showed a radius versus time dependence which agreed with a detonation wave at early times (during the main laser pulse) and with a blast wave at later times. This is illustrated in Fig. 3 for a 120 mTorr ambient gas pressure. In the present experiment, with a much shorter laser pulse, the blast-wave scaling is shown to apply over a large range of laser and ambient conditions.

II. EXPERIMENTAL BACKGROUND

Dark-field shadowgraphy is a very useful diagnostic of the high-pressure coupling fronts. In the present experiment, with a shorter (4 nsec) and more energetic (up to 160 Joules) main laser pulse than in the 1970 experiment, the luminous fronts observed with fast (framing) photography were not very well resolved. However, by using a very short (300 psec) probing laser pulse and dark-field shadowgraphy, we have been able to obtain high resolution (few micron), dual-time photographs of structure in the coupling region.

Dark-field shadowgraphy allows the preferential sampling of the steep-gradient region of an expanding plasma front and permits two-dimensional multiple-time recordings on a single photograph.[4] The dark background also allows one to see faint luminous regions or regions of density variation (e.g., due to photoionization by front radiation) near the coupling region. The diagnostic is thus well suited for studying phenomena in and near the coupling region.

The experimental set-up is illustrated in Fig. 4. The second harmonic probing laser beam is incident from the right, parallel to the target surface.

A 25-cm focal length lens, positioned 50 cm from the target (for one-to-one imaging) is used to collect the light. Probe light that is not appreciably deflected by the plasma is focused by the lens, and blocked by a small opaque mask at its back focal plane. This produces a dark background. However, light that passes through the steep-gradient region (front) is deflected and then is redirected by the lens past the mask and recorded. Thus, a bright profile of the steep-gradient region is recorded on the dark background. The purpose of the mask can be described more quantitatively as filtering out the longer transverse spatial wavelengths. Thus, one records the shorter wavelengths or larger wavenumbers which characterize the steeper gradients.

On most of the shots, two delayed probing laser pulses were used and spaced in time to avoid image superposition. Thus, bright profiles of the coupling-front region were obtained at two times so that front deceleration and break-up evolution could be seen. The probe pulses at these two times were filtered with separate masks. The density of the scattering region was about four orders of magnitude below the critical density of the probing radiation resulting in refraction through very small angles ($\sim 10^{-4}$ radian). This placed a severe restriction on the spatial filtering so that the probe light focused onto the masks had to be placed very close ($\sim$ 100 micron) to the edge of the masks (typically around 1 mm dimension).

III. EXPERIMENTAL STUDIES AND RESULTS

Conditions for the dark-field shadowgraphy studies are summarized in Table I. Data was taken over a large range of laser and ambient gas parameters. The equal-mass coupling radius dependence on laser energy and ambient pressure was checked. The laser irradiance (and thus debris velocity) was varied (at a fixed laser energy) by varying the laser spot size. Although a few shots were taken

with an ambient magnetic field (0.63 kG), the coupling did not appear to be magnetic field dependent at the higher pressures (> .2 Torr) used in the dark-field study. Ripin et al.[5] correlates these data using blast-wave model scaling. We concentrate here on discussing the general features of the coupling shells and the nonuniformities evolving from them.

Table 1 — Dark-field shadowgraphy studies

(VARIATIONS)

- LASER ENERGY (4 TO 160 JOULES)
- LASER SPOT SIZE (.25 MM OR 1 MM)
- AMBIENT PRESSURE (.2 TO 10 TORR)
- AMBIENT COMPOSITION (.9 N_2 + .1 H_2 OR He)
- AMBIENT MAGNETIC FIELD (0 OR .63 kG)

(SPECIAL TARGETS)

- TARGET TILTED ABOUT HORIZONTAL AXIS
- CH TARGETS WITH STRIPES (Al OR Au)

Some of the dependences and structures are presented in the next few figures. See Fig. 5 for example. The main laser beam is incident from the right. The distances can be judged from the 5 mm spacing in the target holder - seen on the left. The ambient gas was 90 percent nitrogen with 10 percent hydrogen (as a spectroscopic diagnostic). The targets were 4.6 micron-thick aluminum foils. The coupling regions (bright rings) are seen at two different times as they expand to the right. There is also a bright patch, due to probe light scattered by debris plasma near the target surface, or due to emitted light in the band pass of the filter on the left, just in front of the target surface. The bright, narrow, curved region of dense, ablatively accelerated target material is seen on the left, going to the left. Figure 5 (shot number 13672) shows the coupling region at 52 nsec and 164 nsec after the peak of the 20 Joule main laser pulse. In this case, the ambient nitrogen/hydrogen gas pressure was 1.5 Torr. One can see a nearly-spherical, sharply-defined coupling shell of thickness about 300 μm. Often the shell exhibits a thin dark region between two bright regions; this is expected when the shell is thin with steep gradients on the outer and inner surfaces. There is some evidence at the later time and larger radius that deviations from the smooth shell are developing. The exposure taken at 52 nsec shows a shell with a radius of curvature of 1 cm and with structure within the shell consistent with gradient scalelengths of only 10^{-2} cm. In order to obtain this exposure, it was necessary to have the focus of the collimated probe beam only 10^{-2} cm from the edge of the mask. Using this information and the 25-cm focal length of the lens, one can place a lower limit on the density sampled.

A method for estimating the minimum density consistent with the dark-field and shell parameters is outlined in the appendix. We note that the second-harmonic probe light must have been refracted in the front region by at least 10^{-2} cm/25 cm or by 4×10^{-4} rad in order to clear the mask and be recorded.

The angle of refraction ϑ is seen to depend on the gradient of the refraction index along the ray trajectory. For a fully-ionized plasma (where electron refractivity dominates) the index is shown in terms of the electron density n and critical density (10^{21} cm^{-3}) n_c at the main laser wavelength. Since refraction is weak one could take the path length d through the shell as the diameter of a chord with the penetration depth s related to d by the sagitta formula. If the penetration depth is about a gradient scalelength L, then n/n_c is of the order of by $\vartheta\sqrt{L/2r}$. Alternatively, if we use Bouguer's relation, which is valid for spherical symmetry, we can express the refraction angle as an integral over radius and thus avoid the problems of working with an unknown ray trajectory. The density ratio n/n_c can than be expressed in terms of the closest point of approach a to the center of spherical symmetry and the impact parameter $b = a\bar{n}(a)$. For a thin shell, a is approximately r, the radius of curvature. For weak refraction by a thin shell, one can expand about the lower limit (a singularity) of the integral and choose an upper limit cut-off to get, $n/n_c \tilde{=} \vartheta\sqrt{L/2r}$. Since $\vartheta > 4 \times 10^{-4}$, we find $n > 10^{17}$ cm^{-3}. Actually, spectroscopy shows that the electron density in the shell is around 10^{18} cm^{-3}, which is substantially higher than our lower limit.

Returning now to a discussion of features observed under different experimental conditions, we consider a shot (number 13630) where the ambient pressure is increased to 3.2 Torr. See Fig. 6. Here, the energy in the main laser pulse was 46 Joules. The observation times were 52 and 96 nsec for this and the remaining shadowgrams. The deviation from spherical symmetry is now apparent. A single protuberance or aneurism is seen to be growing in time. The light-dark-light pattern is seen in both the initial shell and aneurism.

As the ambient pressure is increased still further to 5 Torr, as shown in Fig. 7, the aneurism is clearly developed, even at the earlier time (52 nsec).

For this shot (number 13621), an additional small aneurism is also seen developing at the base of the large aneurism. The energy of the main laser pulse was 38 Joules for this shot. An (out of focus) image of the magnetic induction coil is seen on the right. Possible mechanisms causing the aneurism and front break-up are discussed elsewhere.[5-8] The deceleration of the front could play a role in the break-up mechanism. There is adequate time for the Rayleigh-Taylor instability to evolve, if present, although the development of a single protuberance and the growth of wavelengths so much greater than the front thickness is difficult to understand. Also, because of the heating and mass motion in the decelerating coupling region, free convection could play a role in the front break-up. A periodic structure along the front can be seen on this shot but contributions from the diagnostic cannot be ruled out.

As the laser energy is lowered to 8.6 Joules at the 5 Torr pressure, the front break-up starts to show a more complicated structure as is seen in Fig. 8 for shot number 13642. When the laser energy is lowered still further to 4.1 Joules, as shown in Fig. 9 for shot number 13641, the front shows multiple break-up. The special targets, mentioned in Table I, were also used to provide additional information on the aneurisms. In order to check whether the aneurism is related to the incident laser path, the target was tilted about 15 degrees about a horizontal axis on shot number 13684. The aneurisms appeared in a position more along the target normal than the direction of the incident laser. We also tried to induce aneurisms by using structured targets. A target with 50 micron wide aluminum stripes and a 50 micron spacing on a CH plastic film support was used on shot number 13658. Although about 3 stripes were in the focal region, the aneurisms were only seen in the central region of the front. However, a similar shot (number 13683) with gold stripes (instead of aluminum, which produced larger Z/A variations across the target surface) did

show some aneurisms forming to either side of the central region. This provides some evidence that the aneurisms can be seeded in the target structure.

Another feature, observed on a few shots, was a faint secondary front located just outside of the main front. A disturbed region ahead of the main front could be produced by light emitted from the front or by heat conducted from the front. In this case, the observed image is probably due to probe light being refracted by a gentle (weaker than the shock front) density gradient. Emitted light from the outside region is not a likely contributor since it would be smeared by the motion of this region, whereas the observed secondary fronts appear well resolved.

IV. CONCLUSION

In summary, there are several features that can be easily seen in the dark-field shadowgrams: (1) There is a well-defined, thin, nearly-spherical front or coupling region that is slowing down, indicating mass pick-up, (2) Under some conditions (higher pressure, lower energy and later time) the front shows break-up, or marked departure from a spherical shape, (3) When conditions are just marginal for break-up, the front tends to form a single protuberance or aneurism which grows in time, (4) Further into the unstable region, the front shows multiple break-up, (5) Periodic structure is sometimes seen along the front, and (6) On some shots, a fainter secondary front is sometimes seen ahead of the main coupling region.

Finally, we point out some further areas of promising optical diagnostic development for the NRL HANE simulation. These include: (1) Resonant scattering with a dye laser tuned to an ion resonance. This will extend the studies to lower density and allow us to carry out species-specific scattering. We could, for example, scatter off of particular debris or ambient ions, (2) Imaging the Fourier-Transform plane will allow us to record the

angular scatter of a probe light passing through various structures. This would allow a measure of the plasma power function $P(\omega,k)$. (3) Dark-field shadowgraphy is one example of spatial filtering in the Fourier-Transform plane. There are other selective filter schemes which we could consider. (4) We could utilize the polarizations of scattered probe light to obtain information about structures aligned along the magnetic field or, if the field is large enough, measure the magnetic field itself with Faraday rotation. (5) A longer wavelength laser could be considered for several optical diagnostics of lower density phenomena, and (6) Optical diagnostics being developed to study the Rayleigh-Taylor instability in the ablatively accelerated targets will give information on the diassembly phase.[9] For example, the angular pattern of light scattered, at a steep angle of incidence, from the heated side of the target gives information on a high-density (for optical probing) periodic structure.

ACKNOWLEDGMENTS

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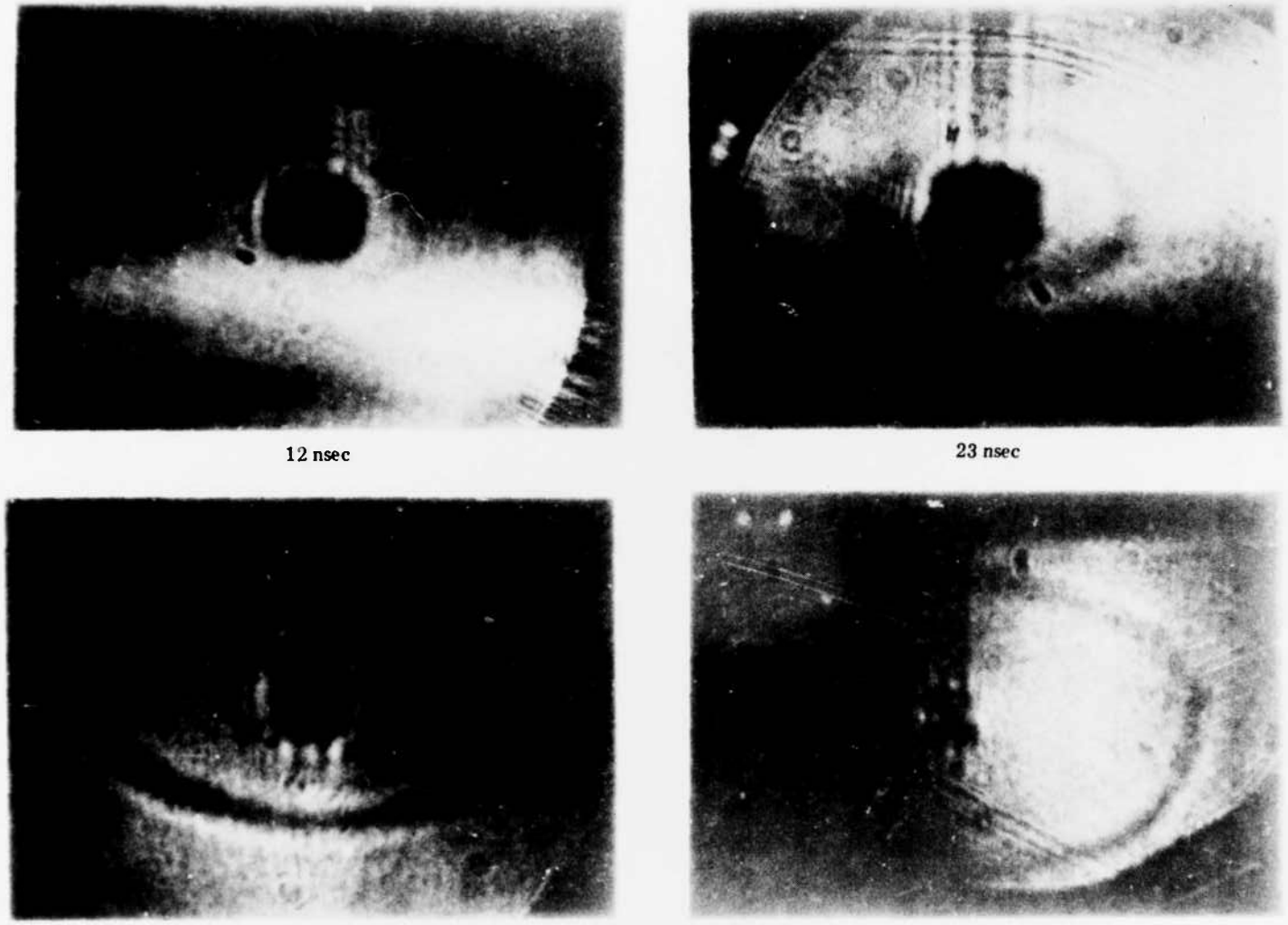


Fig. 1 — Original NRL/HANE Experiment: Single-time, bright-field shadowgrams showing the temporal variation of the coupling region or shock for an ambient nitrogen gas at 200 mTorr.

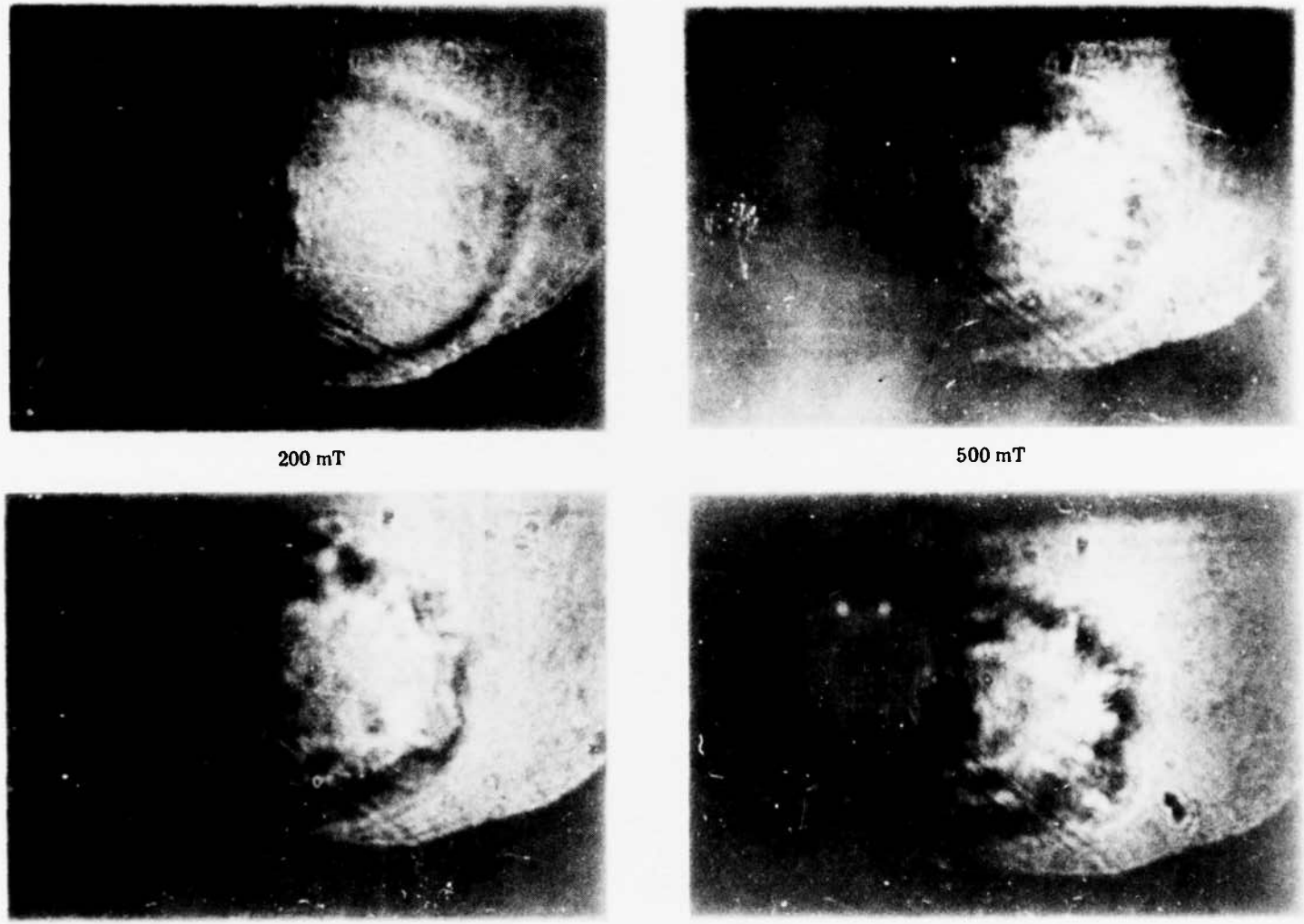


Fig. 2 — Original NRL/HANE Experiment: Shadowgrams showing the pressure dependence of the coupling region at 92 nsec. Above about 500 mTorr, the coupling region shows a turbulent appearance.

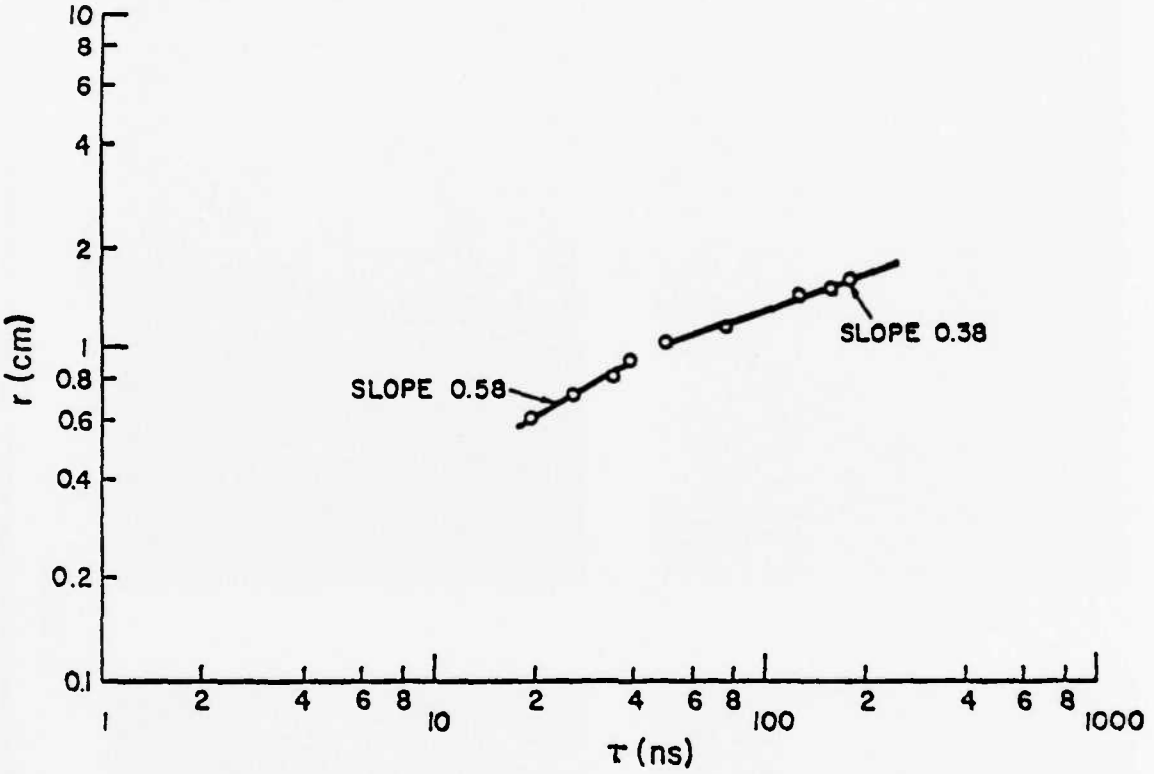


Fig. 3 — Original NRL/HANE Experiment: Radius of coupling region versus time for shots in a 120 mTorr ambient nitrogen gas. The variation follows that of a detonation wave at early times (during the main laser pulse) and follows that of a blast wave at late times.

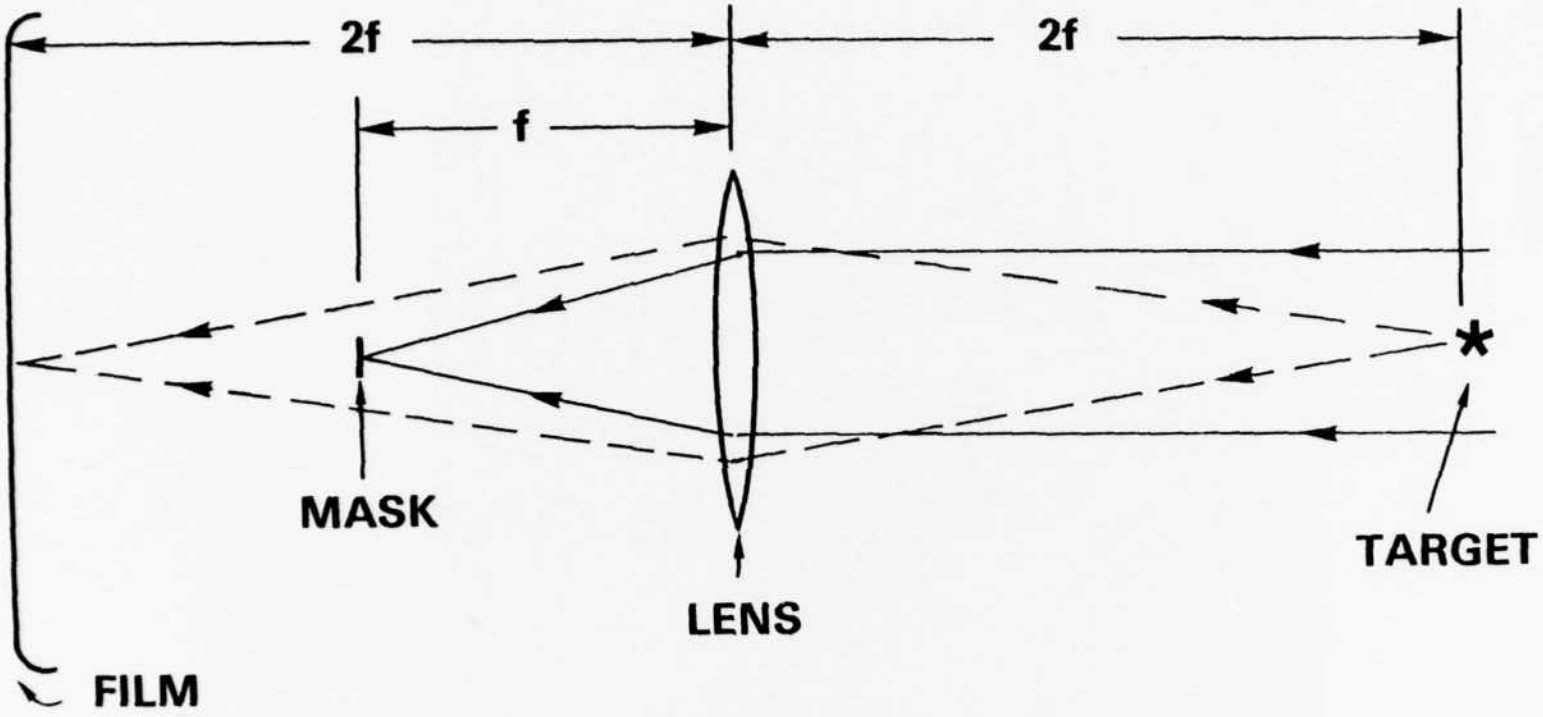
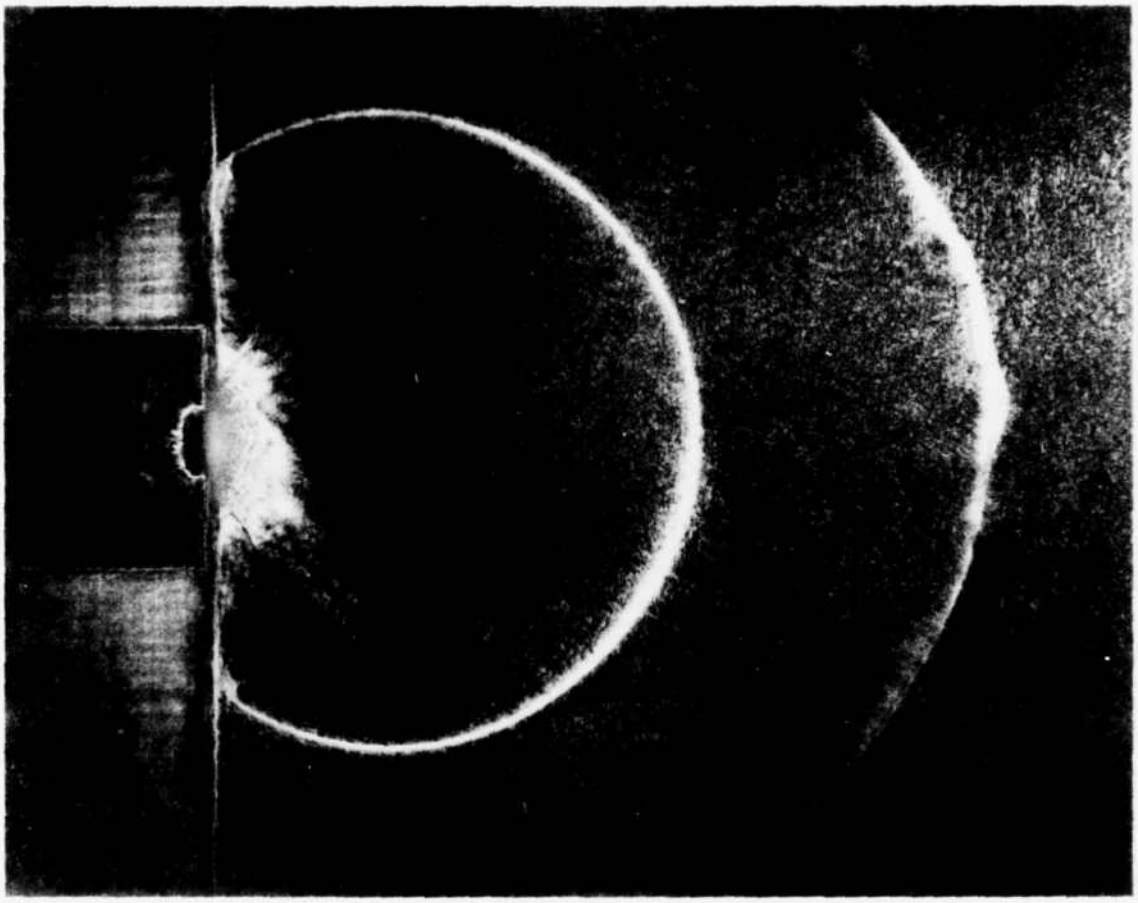
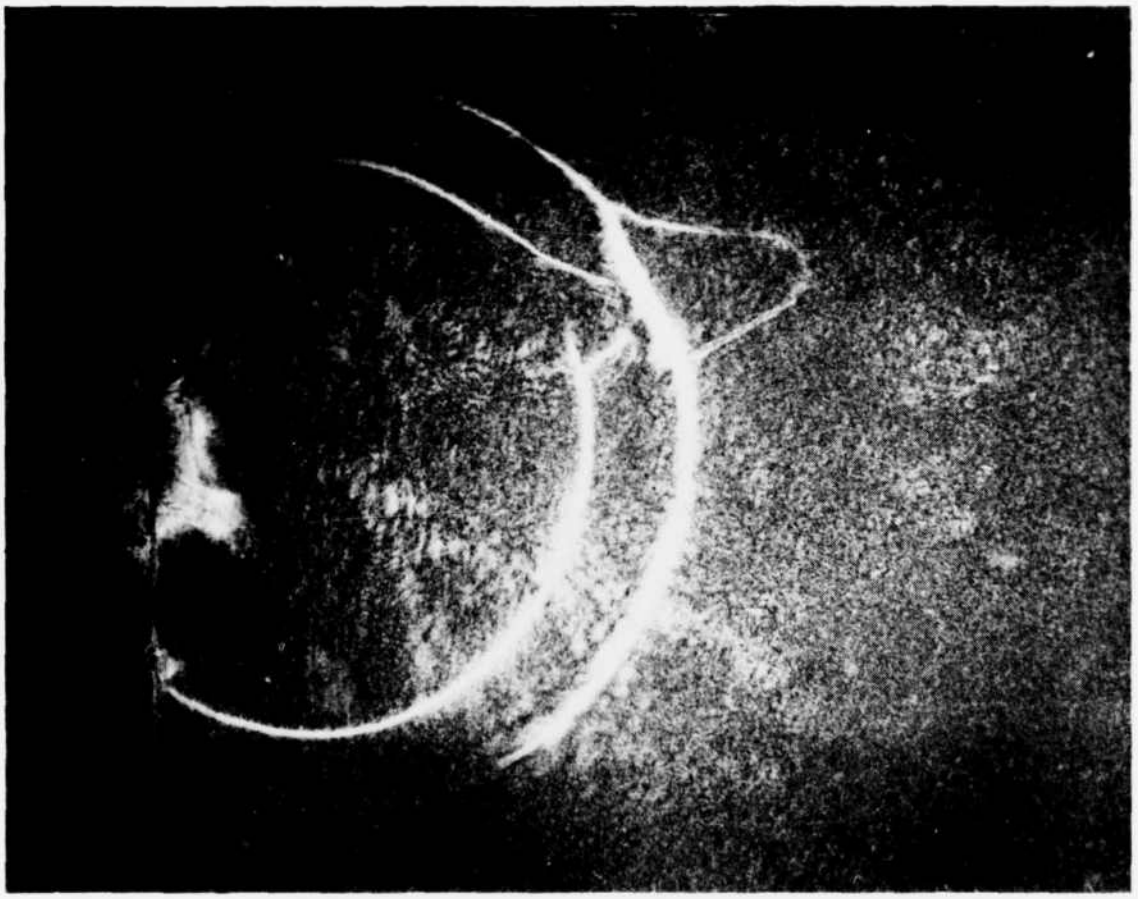


Fig. 4 — Experimental arrangement for dark-field shadowgraphy in the present NRL/HANE experiment. A 300 psec (FWHM) second-harmonic (5270 Å) laser probe was used.



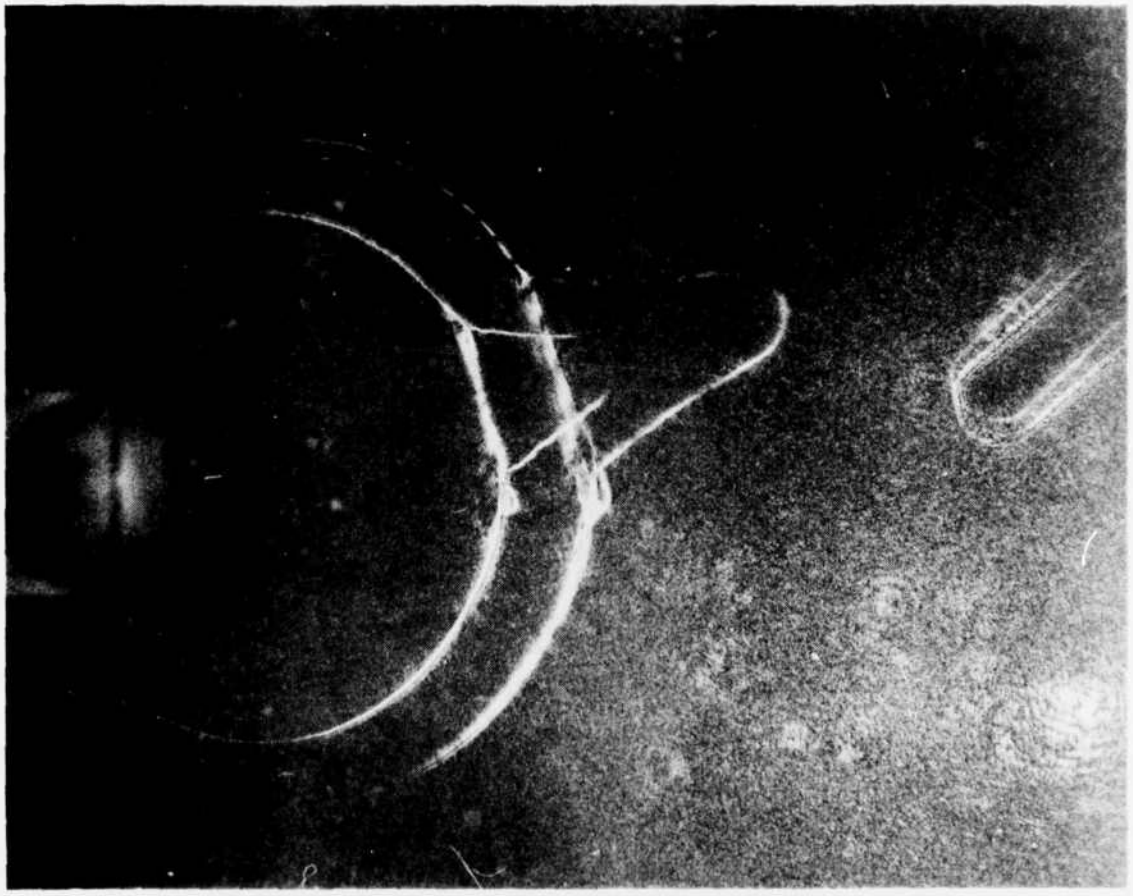
R-1023

Fig. 5 — Dual-time, dark-field shadowgram of a shock front in a 1.5 Torr (90% N_2 + 10% H_2) gas. The observation times were 52 nsec and 164 nsec, the incident laser energy was 20 J, and a 630 gauss magnetic field was present, into the plane of the paper. The shock (coupling region) is seen (at the two times) as the two, thin, large, bright, nearly-circular regions on the right. The smaller, broad, bright region in the right near the initial target is probably due to probe light scattered by slow-moving debris plasma. A smaller, thin, irregular bright region of ablatively-accelerated dense target material is seen on the left. Sizes can be judged by the approximately 5 mm gap in the target holder. Shot number was 13672.



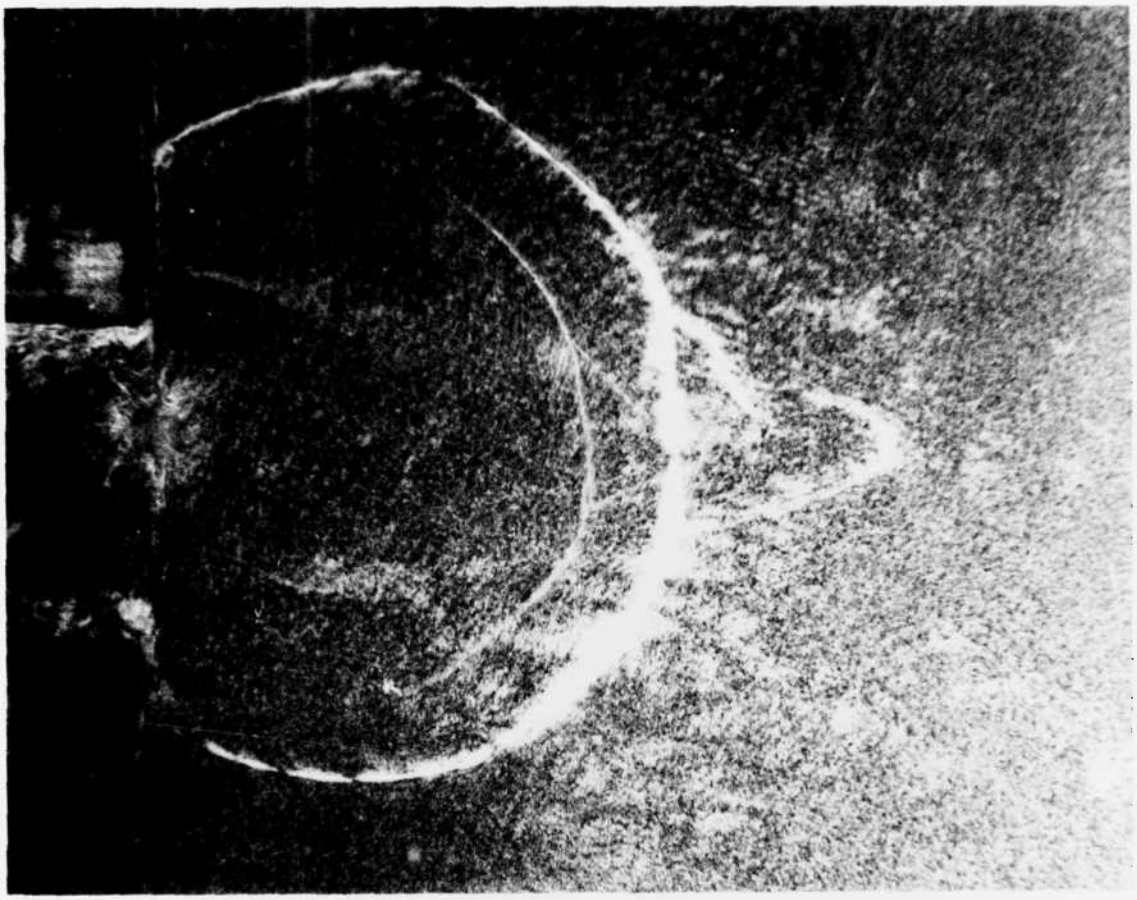
R-1026

Fig. 6 — Shadowgram of a shock front in a 3.25 Torr (N_2,H_2) gas. The laser energy was 46 J and the times were 52 and 96 nsec. A single protuberance or aneurism is seen, growing in time. Shot number was 13630.



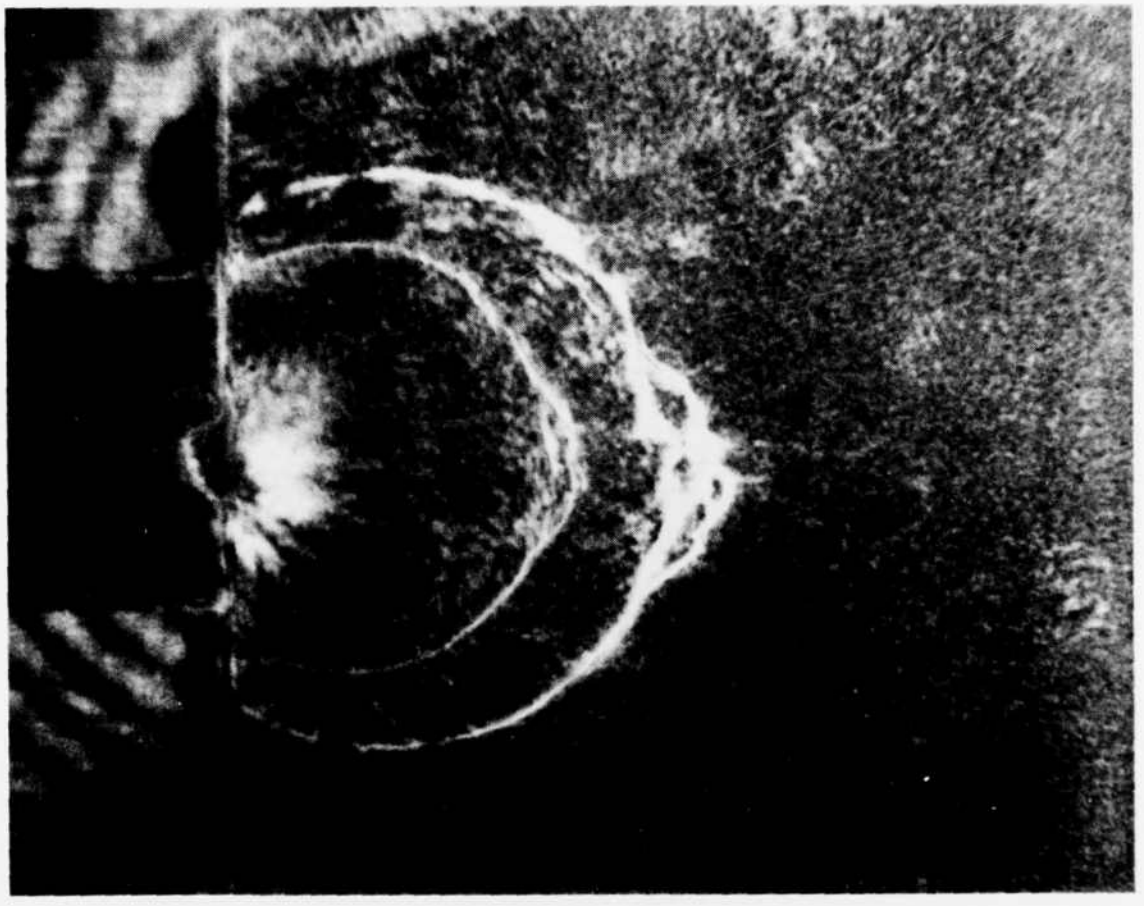
R-1025

Fig. 7 — Shadowgram of a shock front in a 5.0 Torr (N_2,H_2) gas. The laser energy was 38 J and the times were 52 and 96 nsec. The aneurism is clearly developed, even at 52 nsec. Note, the additional, small aneurism developing at the base of the large aneurism. Shot number was 13621.



R-1027

Fig. 8 — Shadowgram of a shock front in a 5.0 Torr (N_2,H_2) gas with less (8.6 J) laser energy on target. Times were 52 and 96 nsec. The aneurism shows a more complicated structure. Shot number was 13642.



R-1024

Fig. 9 — Shadowgram of a shock front in a 5.0 Torr (N_2,H_2) gas with still less (4.1 J) laser energy on target. Times were 52 and 96 nsec. Note the complicated shock break-up, showing the growth of multiple aneurisms. Shot number was 13611.

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Appendix: Density Estimate from Refraction

I. Angle of refraction (second harmonic probe)

$$\vartheta = \int |\nabla \eta| ds; \quad \eta \equiv \ell n \bar{n}; \quad \bar{n} = \sqrt{1 - n/4n_c}$$

II. Spherical shell $(n/n_c = \exp -(r-r_o)/L)$

A. Sagitta Formula

$$d \tilde{=} \sqrt{8rs}$$

$$\frac{n}{n_c} \tilde{=} \frac{rL\vartheta}{\sqrt{2rs}} = 4\sqrt{\frac{L}{2r}}\,\vartheta, \text{ if } s = L$$

B. Bouguer's Relation $(b = a\bar{n}(a) = r\bar{n}(r)\sin \angle(R,r)$

$$\theta = \pi - 2b \int_a^\infty \frac{dr}{r\sqrt{r^2\bar{n}^2(r) - b^2}}$$

$$\frac{n}{n_c} \tilde{=} \sqrt{\frac{L}{2a}}\,\theta \text{ , for } \theta << 1 \text{ and } L/a,\ L/r_o,\ (a-r_o)/r_o << 1$$

III. $n > 10^{17}$ cm^{-3} for $\theta > 10^{-2}/25 = 4 \times 10^{-4}$ and $n_c = 10^{21}$ cm^{-3},
$L = 10^{-2}$ cm, $r = 1$ cm

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