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A Pulsed Nitrogen Laser for Optical Plasma Diagnostics

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A nitrogen laser oscillator-amplifier system has been constructed for use as a fast pulsed light source for schlieren, shadowgraph, Moiré-Schlieren, or interferometric diagnostics of pulsed plasmas. It utilizes an atmospheric pressure nitrogen laser as an oscillator and a low pressure transverse discharge as an amplifier. The output beam has a rectangular cross section with dimensions 5mm x 15mm, a pulse length of about 1 nsec, and is of sufficient optical quality that it may be used for interferometry. The beam energy is about 1 mJoule per pulse.

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TABLE OF CONTENTS

A-1

A PULSED NITROGEN LASER FOR OPTICAL PLASMA DIAGNOSTICS

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I. INTRODUCTION

A pulsed laser light source was needed for diagnostics of the dense Z-pinch plasmas produced by the NRL ZFX experiment[1]. The laser was required to have a pulse length of less than 1 nsec in order to freeze the rapidly changing conditions in the pinch, a coherence length suitable for interferometry, and sufficient power to overcome the intense continuum radiation from the plasma.

The required short pulse can be achieved with the typical atmospheric pressure transverse discharge nitrogen laser, but the beam has poor optical quality[2]. A low pressure nitrogen laser has the necessary optical quality but at the expense of an increased pulse width (at least several nsec)[3,4]. While it is possible to build an atmospheric pressure, short pulse laser of interferometric quality[5], a more efficient method is to use an oscillator-amplifier system[2,6,7,8,9,10,11]. This is the approach described in this paper. The beam is generated by an atmospheric pressure transverse discharge laser, improved by spatial filtering, and then amplified by a single pass low pressure transverse discharge amplifier.

II. OSCILLATOR

The oscillator was built by F. Sandel, and utilizes a Blumlein pulse line constructed from 0.7 mm thick fiberglass printed circuit board material. The construction is pictured in Figure 3. The line is split on the upper side, and is an unbroken conductor (represented in the figure by a dotted line) on the opposite side. The electrodes are aluminum 9.2 mm thick, fully radiused, and pressed against the printed circuit board by a larger lucite plate above. They are separated to form a discharge gap about 4 mm wide. Adjustment screws make it possible to finely adjust the plates for parallelism. This adjustment, once set, rarely needs to be disturbed. It is made by watching the discharge from above and setting the plates to obtain the most uniform discharge. The nitrogen working gas (Ultra High Purity Grade, 99.995% pure) is delivered straight from the bottle through a hole in the upper lucite cover and flows freely out both ends, displacing atmospheric air in the process. A flow rate of 1.0 SCFH is used, but is not critical.

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The oscillator is switched by a spark gap having 12 mm diameter brass electrodes with a midplane tungsten needle held at half the potential by 100 MΩ resistors. In order to assure the switch can be triggered with low jitter, it must be run at a potential just below self-break (~14 kV, which is "32" on the power supply dial), and the needle must be sharp. If the needle is removed for sharpening, it will be necessary to reset the electrodes afterwards, since the needle rarely returns to its previous position. The gap should be about 2-2.5 mm wide, with the needle centered, and the gap pressurized with nitrogen to 10 PSIG. Both electrodes have screwdriver adjustments to allow this. The voltage should not be allowed to run above 15 kV, as this is near the breakdown for the fiberglass insulation of the Blumlein line. (If a breakdown does occur the resulting damaged insulator can be repaired with RTV.)

The oscillator is fitted with a mirror on one side of the discharge cavity, which effectively doubles the length of the cavity. This mirror rarely needs adjustment. If it does, however, it is sufficient to simply look along the channel and align the reflection of the discharge electrodes with the electrodes themselves. We have also tried aligning the mirror by watching the output laser pulse, but neither method seems to offer great advantages. The emitted beam is more divergent in the horizontal plane (parallel to current flow) than in the vertical. This is obvious by just looking at the beam at points farther from the laser, or by observing the burn spot made at the focal plane of the 50mm lens. A photodiode is oriented to look at a small fraction of the beam tapped off by a microscope slide. The output of this photodiode is positive and about 10 volts and may be used as synchronization pulse. Because the output is very narrow in time, it is useful to integrate it with a 50-200 nsec integrator to make it more visible.

III. AMPLIFIER

The amplifier (Figs 2a,b) design is similar to the oscillator described by Fisher et. al.^{3,4}. Two rods 2.54 cm in diameter and 45.7 cm long serve as the electrodes. Their facing sides have been planed off to produce a flat about 2 cm. wide, and the edges are rounded to approximate a Bruce profile^{12} Moiré-Schlieren. The electrode gap is 2 cm. The electrodes are mounted in a lucite tube that is 5 cm id and 61 cm long and fitted with 2.54 cm diameter high quality quartz windows. These windows are canted about 2° from the axis perpendicular to prevent the amplifier from oscillating spontaneously. (Somewhat surprisingly, using anti-reflection coated windows alone was insufficient.)

Electrodes of both brass and carbon have been tried. The brass electrodes produced highly non-uniform discharges even with a coating of aquadag. With the carbon electrodes it is possible to find a range of pressures and operating voltage that results in many small arcs that merge to a sufficiently uniform discharge. Two sets of carbon electrodes have been tried. One set had nearly flat facing surfaces with only slightly rounded edges, and produced a discharge that uniformly filled the 18 mm wide region between the electrodes. This amplified that was almost as wide as the electrode width. The other set had a smaller radius of curvature, produced a 5 mm diameter discharge, and amplified a correspondingly tighter beam.

The amplifier is electrically driven by a parallel-plate pulse line having a width of 44 cm (i.e. almost equal to the electrode length), as shown in Figure 2b. Each side of the line has a characteristic impedance, $Z_0 \sim 1.6\ \Omega$, and is 1.2 meters long. It is doubly folded to make a compact structure that extends only about 30 cm to each side of the discharge tube. The dielectric is several layers of Mylar with a total thickness of 1.6mm. This line is pulse-charged with a quarter period of 80 nsec from a bank of eleven 2700 pf @ 40 kV doorknob capacitors. The discharge tube (i.e. laser) self-breaks with about a 10 nsec jitter. The peak amplifier current is about 20kA, so the current density for the smaller radius electrodes is about 900 $\mathrm{Amp/cm^2}$ and for the flatter electrodes about a factor of three smaller. As expected, the amplified light beam is distinctly less intense in the latter case.

Because the oscillator output must be synchronized with the peak amplifier discharge current to within about ± 2 nsec it is necessary to provide a precise trigger. This is achieved with the electrical circuit shown schematically in Figure 3a, and depicted in Fig 3b. An external trigger fires the amplifier switch which simultaneously starts the 80 nsec long charging cycle of the pulse line and sends a pulse down two 80 nsec long RG/8 cables which are connected across the amplifier switch output. One of these cables fires a sparker placed at one end of the amplifier just as the amplifier voltage is reaching maximum, causing the amplifier discharge to fire with about 1 nsec jitter. The second cable triggers the oscillator switch, which produces its beam within about 1 nsec. The cables may be pruned to obtain the optimum performance.

The entire N_2 laser system is mounted inside an electrically shielded box. The box also prevents dust from collecting on the laser components. The four sides of the box and the top are readily removable with Dzus fasteners to allow access to the laser. Two photos of the laser system is shown in Figure 4a and 4b.

IV. OPTICS

The optical path is shown schematically in Fig 5. The output of the oscillator reflects from a 45° dielectric mirror that is nearly 100% reflecting at 337 nm, but transparent in the visible. At this point, a He-Ne laser beam is introduced to lie along the N_2 laser path for alignment purposes. The beam(s) are brought into focus by a 50 mm focal length quartz lens, and spatially filtered with a 10 μ m diameter pinhole. This pinhole may be moved by screws along two axes perpendicular to the beam. The adjustment is exceedingly delicate, and it is difficult to find the right spot with the He-Ne beam if it is lost. (A 10 μ m hole is not very large, and the focus of the He-Ne laser beam is only about 30 μ m in diameter.)

The N_2 laser focal spot is larger, measuring about 100 μm x 250 μm, but since it may only be seen when the laser is pulsed, it is usually easier to locate the pinhole using the He-Ne beam. There is also an adjustment to place the pinhole in the focal plane of the lens. This can be done by carefully observing the size of the burn mark made by the oscillator pulse on a target, such as exposed polaroid film, that is mounted in place of the pinhole. Once so positioned, it should not be necessary to change this setting.

Light passing through the pinhole is collimated by a 175 mm focal length quartz lens, which forms a beam about 2 cm in diameter, and is directed by a mirror through the amplifier. The gain profile of the amplifier discharge is reasonably uniform in the vertical direction, filling the 20 mm space between the electrodes, and about 5 mm wide in the horizontal direction (in the case of the more curved electrodes). Thus the amplified beam is rectangular in cross-section. With the flatter electrodes the output beam was wider but lacked the intensity required for interferometry.

To check for laser operation it is convenient to place a fluorescent target such as exposed Polaroid film inside the laser cabinet covering the exit port. As the inside of the cabinet is dark, one can easily observe the output while operating the laser. An ill-defined wash of white or bluish light on the screen indicates only that one is seeing the discharge light. On the other hand, bright well-defined spot indicates the amplifier is working properly.

If no amplified pulse appears, there are several things to check. First the oscillator gas should be checked with the flow meter. One may then try turning the oscillator voltage up a bit (Not over 15 kV!) and varying the amplifier fill pressure. The amplifier runs with a steady flow of gas through the discharge chamber, so the exhaust valve leading to the pump should be fully open. The pressure should be set to about 60 Torr on the gauge, but it may be varied in the 40-80 Torr range. If the pressure is wrong, the discharge tends to arc.

V. INTERFEROMETER

The interferometer (Fig 6) is in a Mach-Zehnder arrangement with the reference beam displaced only 16 mm to the side of the scene beam. This unconventional feature allows both beams to pass through the 50 mm diameter windows of the ZFX vacuum chamber but only the scene beam to intercept the fiber. The reference beam is off to the side and is undisturbed by the plasma until quite late in the discharge. This setup was adopted owing to the practical difficulty of maintaining two beam splitters and two mirrors aligned. An incidental advantage is that the optical paths are automatically compensated and equalized as both pass through the same windows. The latter is necessary because of the short (< 1 mm) coherence length of the laser.

Two rigid stands were constructed, with one beamsplitter and one mirror mounted on each stand. These optics may be pre-aligned on the bench and then moved to the experimental area. The beamsplitters are on quartz substrates with a small wedge angle so the transmitted beam is slightly deflected. The reflecting surface should be placed to the outside when orienting the beamsplitters (reflecting surface facing the laser on the input side, and facing the camera on the output side). In this orientation the transmitted intensity of the two beams is nearly equal.

The two beams emerging from the first beamsplitter/mirror set must pass through the 50 mm diameter vacuum windows and the scene beam must be centered in the window to illuminate the fiber. The 16 mm diameter beams should be separated by 16mm to prevent both overlapping and vignetting by the edges of the vacuum windows. The scene and reference beams are recombined by the second beamsplitter-mirror set and pass on to a camera. A 350 mm focal length lens is placed after the beamsplitter and focuses the fiber onto the film. By placing a small aperture at the focal point of the lens much of the plasma light will be excluded but the laser beam will pass through through without attenuation.

To align the interferometer it is best to first ensure that the scene beam passes through the first beamsplitter and then through the center of both of the vacuum windows. An auxiliary gas laser directed backward through the chamber is helpful. Alignment is easier if a target is installed in place of the fiber. Small adjustments may be made by the mirror adjustment screws on the last mirror on the laser stand. Rotating the entire beamsplitter/mirror assembly will change the separation of the beams slightly, but it will be close enough if the edge of the stand is parallel to a radius of the ZFX load chamber. The parallelism of the two beams may now be adjusted with the mirror adjustment screws on the input side. The two beams should now pass through the two holes in the mask on the output side. Getting this setting right is easier if the input beam aperture is decreased using the iris installed on the input side stand.

The trick in alignment at the output side is to make sure that the scene beam, which reflects first from the mirror, hits the beamsplitter in the same spot as the reference beam. This may be adjusted using the mirror adjustment screws. Once this is set the beams should be observed from as far away as possible, and the beamsplitter screws adjusted to bring them together. The fringes should then appear readily. This is all done without the focussing lens in place. It may then be installed, followed by the camera and aperture. In order to exclude plasma light we found it necessary to install two wide band filters and one narrow band filter in front of the camera. Finally, it is advisable to put a shutter in the beam, to prevent exposure of the film during charging of ZFX in case the laser prefires.

VI MOIRE SCHLIEREN

Moiré-Schlieren interferometry is a technique for measuring the electron density gradient in a plasma. Its output is an image of the plasma, formed in interference fringes, that appear quite similar to the fringes of ordinary interferometry. The displacement of the fringes is proportional to the line-of-sight integral of the transverse (to the line of sight) electron density gradient in the direction perpendicular to the fringes. Moiré-Schlieren was chosen over ordinary interferometry because the beam quaility requirements are less demanding, the hardware is simpler and cheaper, and the setup is easier.

The plasma region is illuminated by a collimated beam of monochromatic light from a laser. After passing through the plasma, the beam passes through a pair of identical coarse transmission gratings called "Ronchi rulings". These are separated by a small distance D, and oriented perpendicular to the optic axis, but rotated about the optic axis so that their rulings depart from parallelism by a small angle α. The beam is then focussed onto a screen by a simple lens, and the first order interference maximum allowed to pass through a small aperture in the screen. The recording film is placed farther on, so that it is in an object-image relationship with the plasma region (Figure 7).

While it is possible to analyse a Moiré-Schlieren system by invoking ray optics and treating the rulings as venetian blinds that simply cast overlapping shadows, this approach lacks insight. In particular it does not explain why the first interference maximum should be chosen. A more illuminating approach is to think of the various interference orders emerging from one of the gratings as being simple plane waves displaced in angle from the laser beam direction by the usual interference angles $\theta_n = \sin^{-1}(n\lambda/d)$, where λ is the wavelength, d the grating spacing, and n is an integer identifying the order. Since the two gratings are rotated with respect to one another by the angle α, the first order beam from one will not be parallel to that from the other, but have an angle $\beta=\alpha\theta_n$ between them (for $\theta_n << \alpha << 1$). These two beams are coherent, overlap in space, and have a small angle between their wavefronts, so they will interfere, producing a pattern of straight parallel fringes on a screen placed in their path. The fringe separation is simply $s = \lambda/\beta$. Interposing a lens in the path of the beams changes the fringe spacing to $s' = Ls/f$ where f is the focal length of the lens, and L the distance from focal spots to the image plane.

To include the influence of the plasma, it is assumed the incident monochromatic beam has been deviated by refraction in a density gradient, and therefore enters the gratings at a small angle δ with respect to the optic axis (Fig. 8). For the first order beams, $\lambda/d = \sin(\gamma)+\sin(\delta)$. If the angle γ has been selected to give an interference maximum on a distant screen, then the condition of a maximum is:

$$\Delta L = n\lambda = D/\cos\gamma - D/\cos\delta + (b + c)\sin\delta, \qquad (1)$$

where:

$$b = D\tan\delta, \text{ and } c = D\tan\delta. \qquad (2)$$

With $\delta << \gamma$, the condition for a change of optical path of m wavelengths between the first order beams from the two rulings is

$$m\lambda/D = \gamma\delta, \qquad (3)$$

and $\gamma = \lambda/d$. Thus we obtain $\delta = md/D$, which is just the result with ray optics if the condition is imposed that the shadows of one grating coincide with those of the other. A beam deviated by refraction in the plasma by an angle δ will therefore be split by the two gratings into two first order interference maxima, and these will arrive at the distant screen (or film plane) one wavelength out of step compared to an undeviated ray. Thus a shift of one fringe will be seen at that position in the image of the plasma.

To relate the ray deviation angle δ to the electron density gradient along the ray path, we must first note that the angular deviation $d\delta$ of a ray passing in the Z direction through a region having a density gradient in the y - direction is:

$$d\delta/dZ = dn/dy. \qquad (4)$$

For electromagnetic radiation with frequency ω well above the plasma frequency ω_p, the index n is given approximately by:

$$n \approx 1 - (2\pi c^2 n_e/m\omega^2), \qquad (5)$$

where m and n_e are the mass and number density, respectively, of the electrons. Substituting in Equation 4, we obtain:

$$d\delta/dz = c\lambda^2(dn_e/dy), \qquad (6)$$

where $c \equiv - 4.477 \times 10^{-14}\text{cm}^{-1}$, and λ is the wavelength of the laser radiation. Integrating along the ray path to obtain the total deviation of the ray yields:

$$\Delta\delta = c\lambda^2 \int(dn_e/dy)\, dz. \qquad (7)$$

Combining Equations 7 and 3, we find the condition for a fringe shift of m fringes is

$$\int (dn_e/dy)\, dz = md/c\lambda^2 D. \qquad (8)$$

As an example, consider the "halo" around a 50 μm diameter fiber and assume that

$$(dn_e/dy) \sim 10^{20}\ \mathrm{cm}^{-3}/10^{-2}\ \mathrm{cm} \sim 10^{22}\ \mathrm{cm}^{-4}.$$

This gradient will only be felt in a region of about the size of the radius, so

$$\int (dn_e/dy)\, dz = 10^{20}\ \mathrm{cm}^{-4}.$$

For a grating with 20 lines/mm, $d = 5 \times 10^{-3}$ cm, and if it assumed that $D = 1$ cm, then $m \approx 1$. Thus in the vicinity of the fiber the deviation would be about one fringe width.

VII SUMMARY & ACKNOWLEDGEMENTS

The N_2 laser oscillator/amplifier system is now ready for deployment. The authors *are grateful for the assistance of* Mr. K. A. Gerber and the technical assistance of Mr J.P. Picciotta, Mr. D.R. Evenson, and Mr. K.M. Coffey. This work was supported by the Office of Naval research and the U.S. department of Energy.

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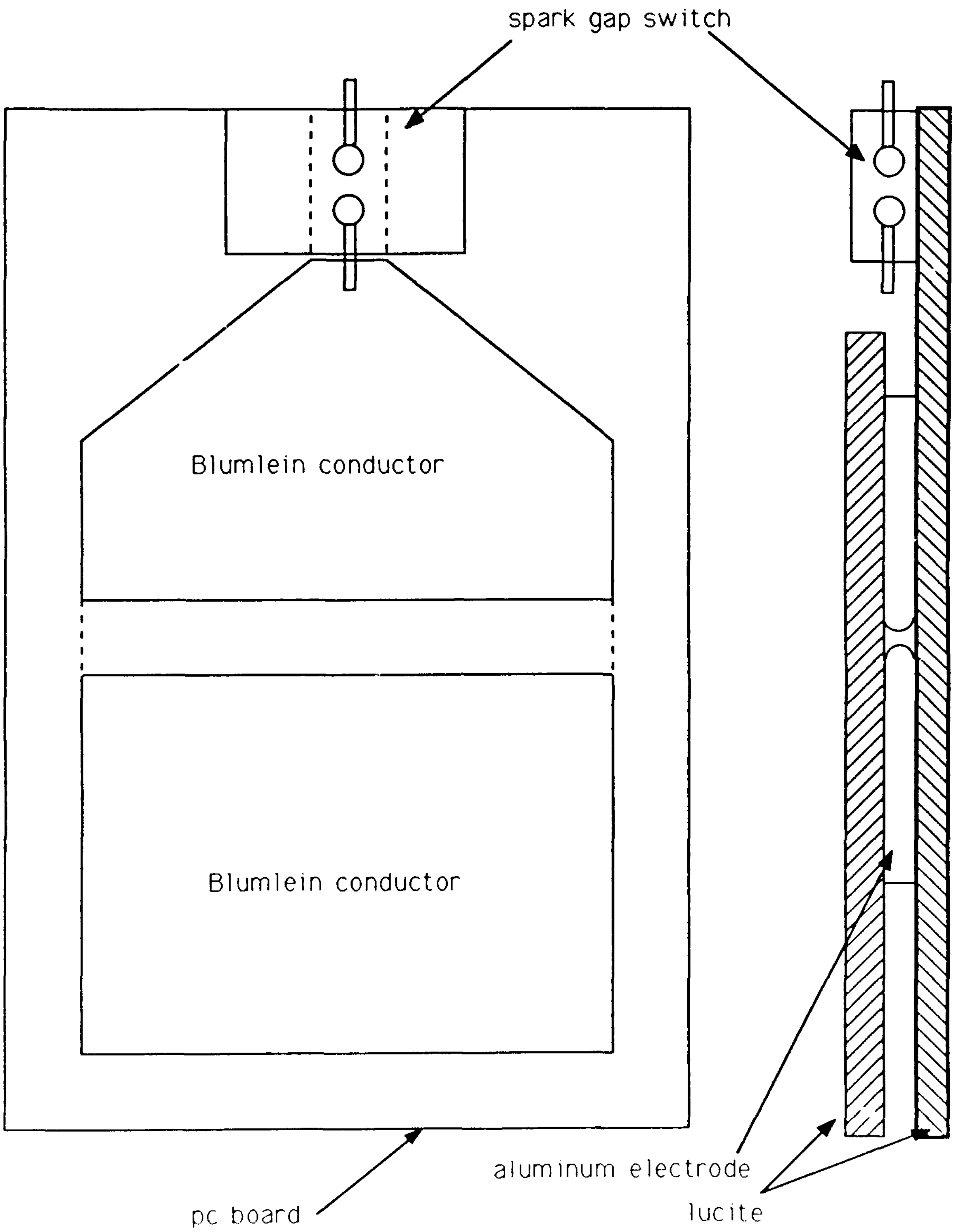

Figure 1: The Nitrogen laser oscillator

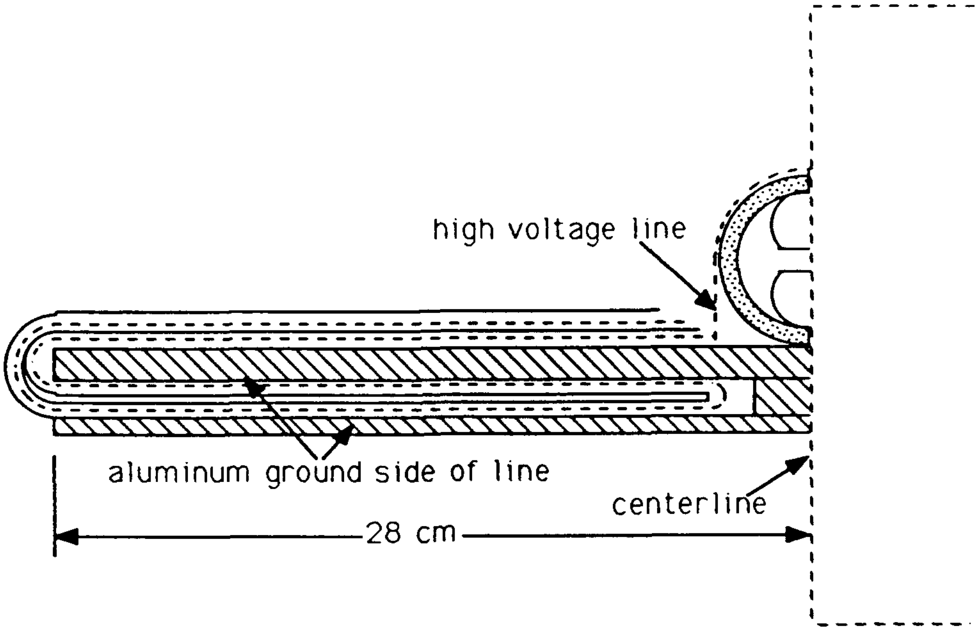

Figure 2a: ***Cross section of the nitrogen laser amplifier showing the doubly folded parallel plate line, the discharge tube, and the electrodes.***

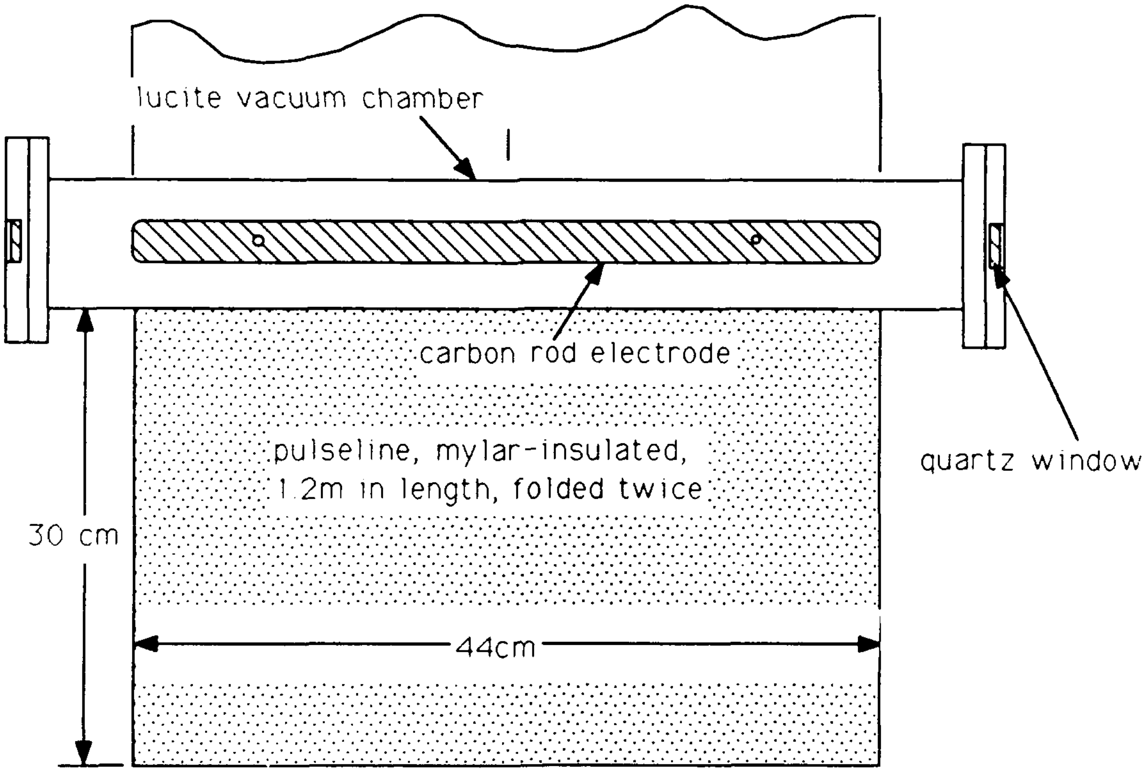

Figure 2b: Top view of nitrogen laser amplifier.

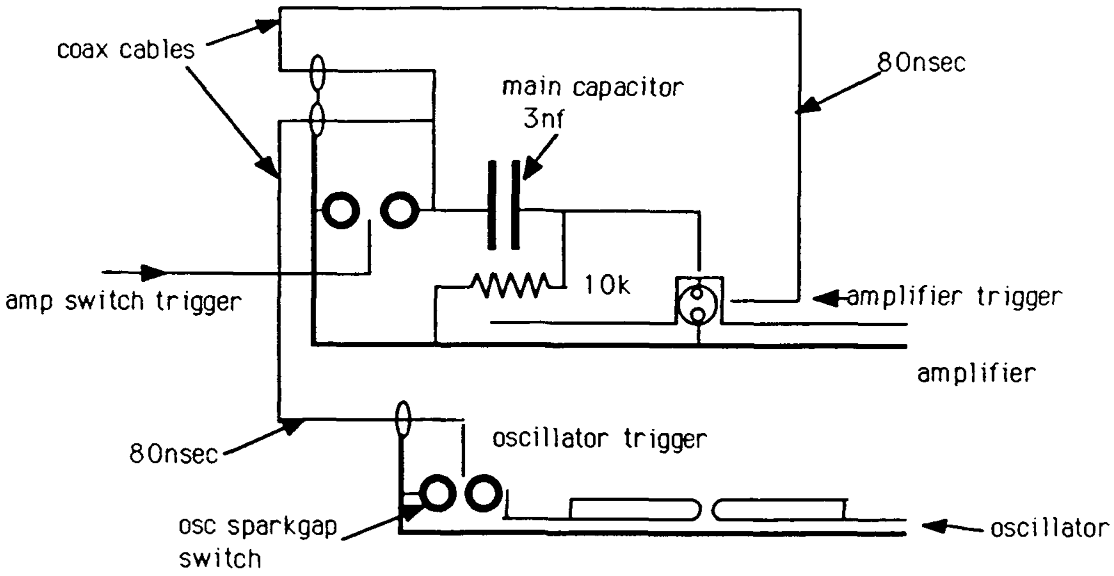

Figure 3a: Complete circuit of nitrogen laser amplifier plus oscillator

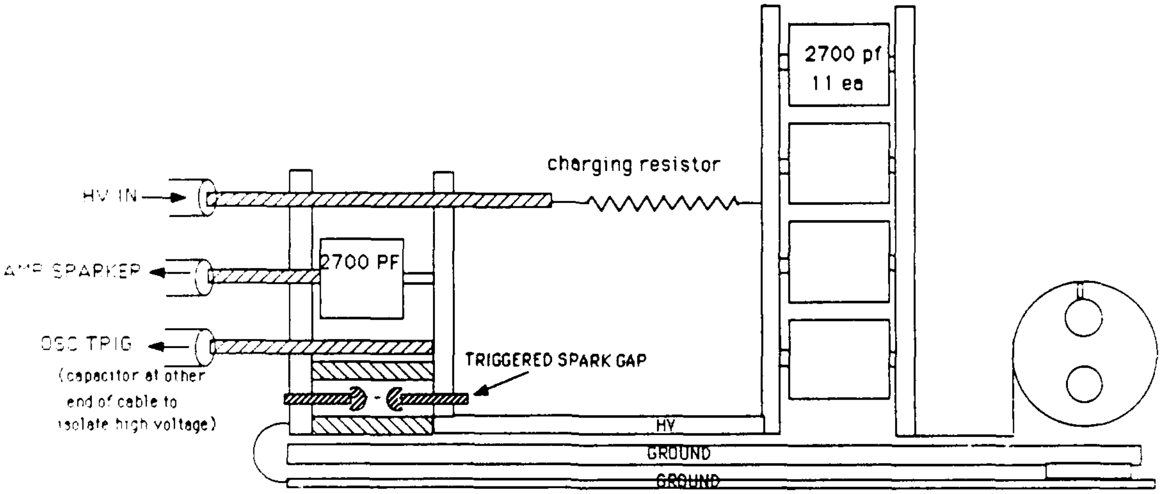

Figure 3b: Switching circuit for amplifier.

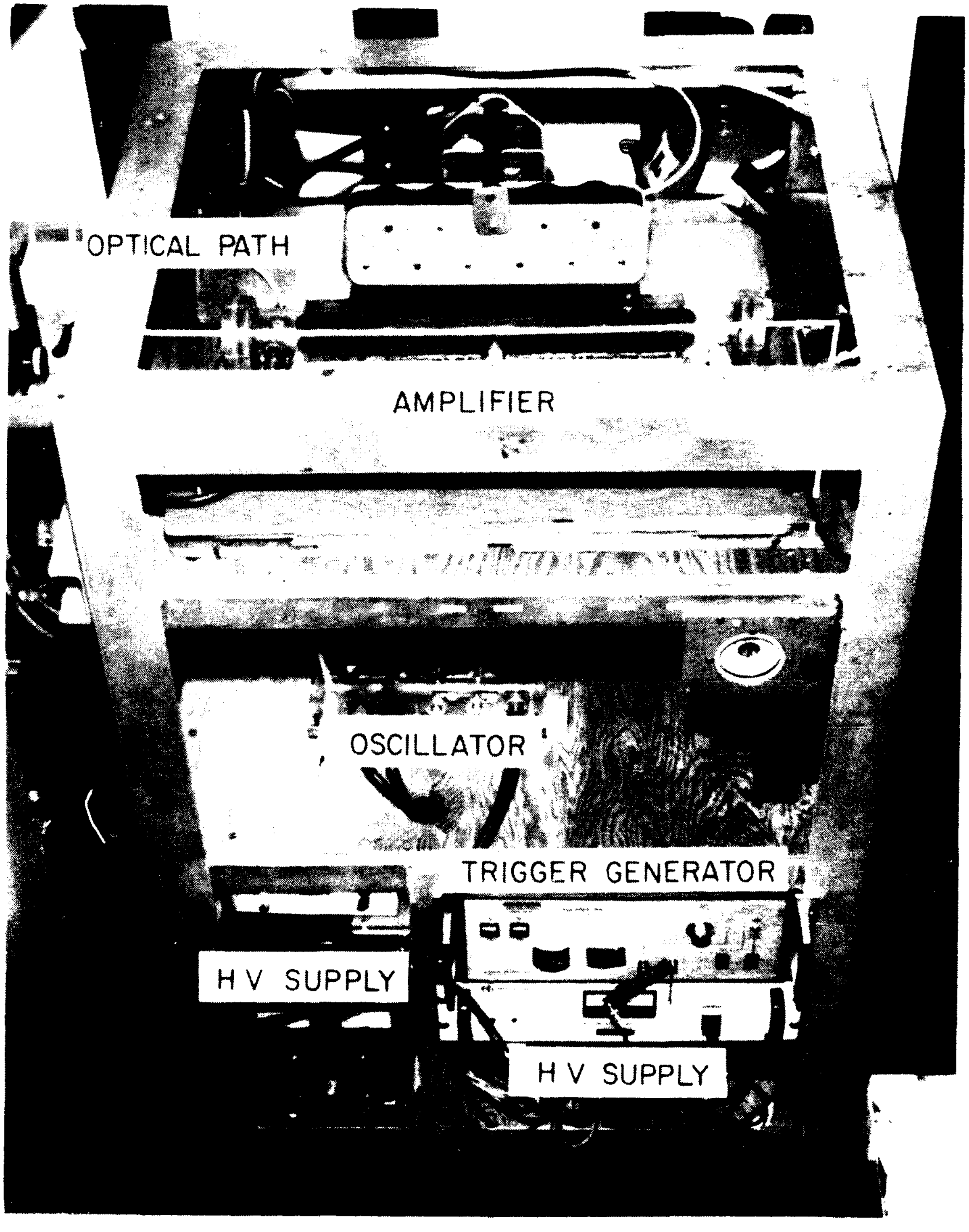

Figure 4b: *Photo of N_2 laser system, top perspective showing the support structure, electronic components and relative positions of oscillator/amplifier. The sides of the structure, normally in place to form an electrically tight box, have been removed.*

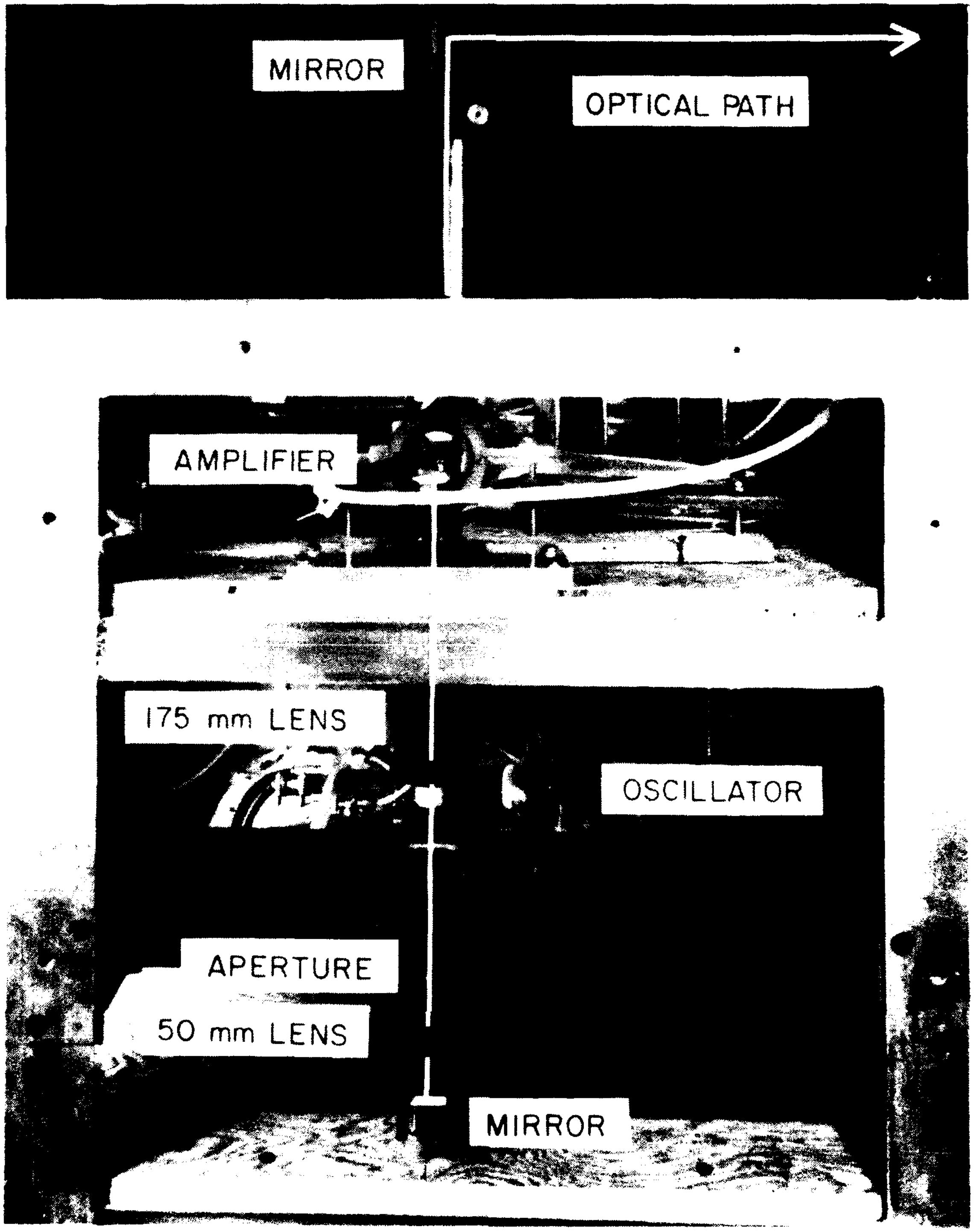

Figure 4b: Photo of N_2 laser system showing optical path.

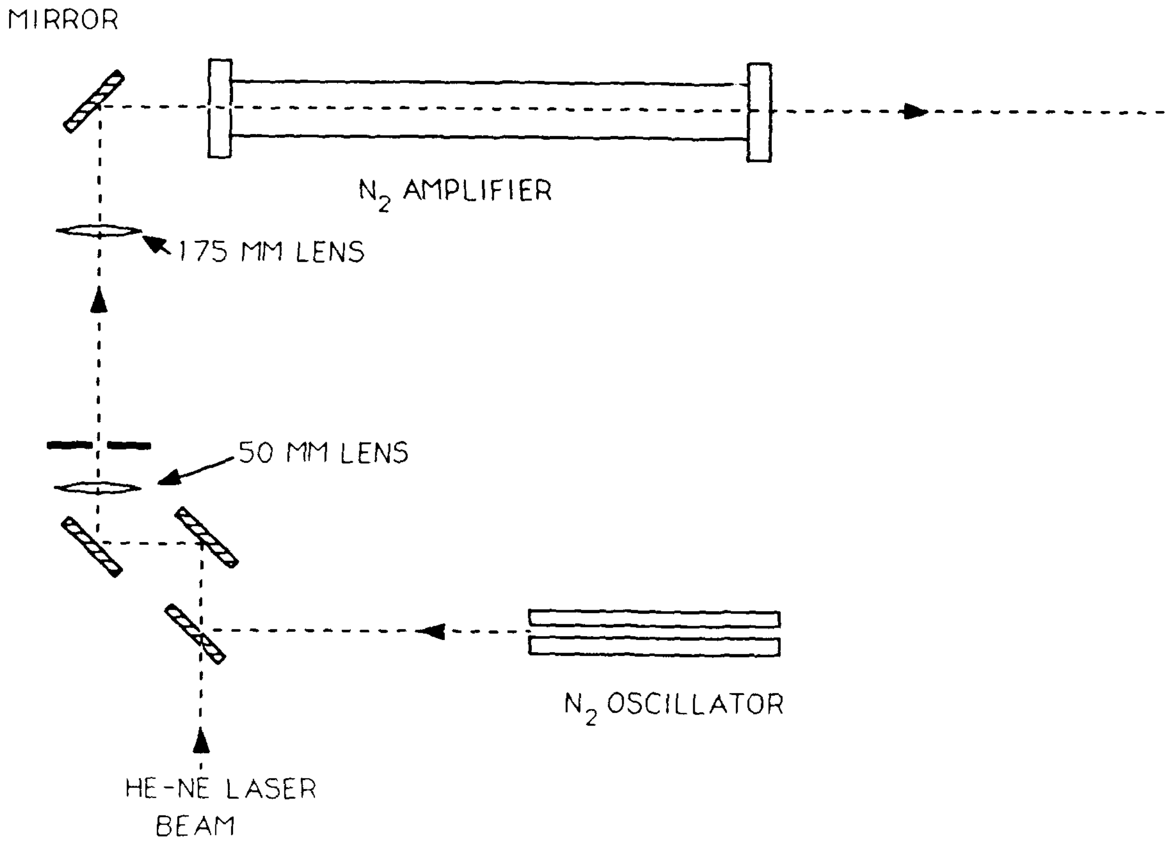

Figure 5: Optical path of oscillator/amplifier system.

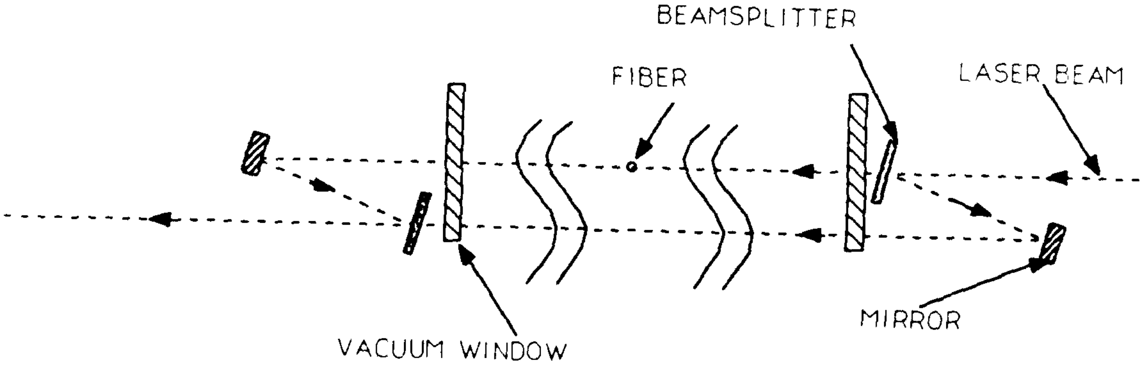

Figure 6: Mach-Zehnder interferometer.

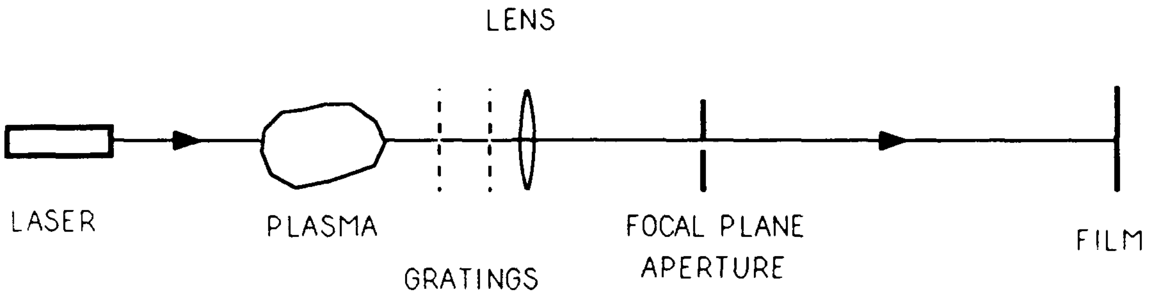

Figure 7: Moiré-Schlieren optics.

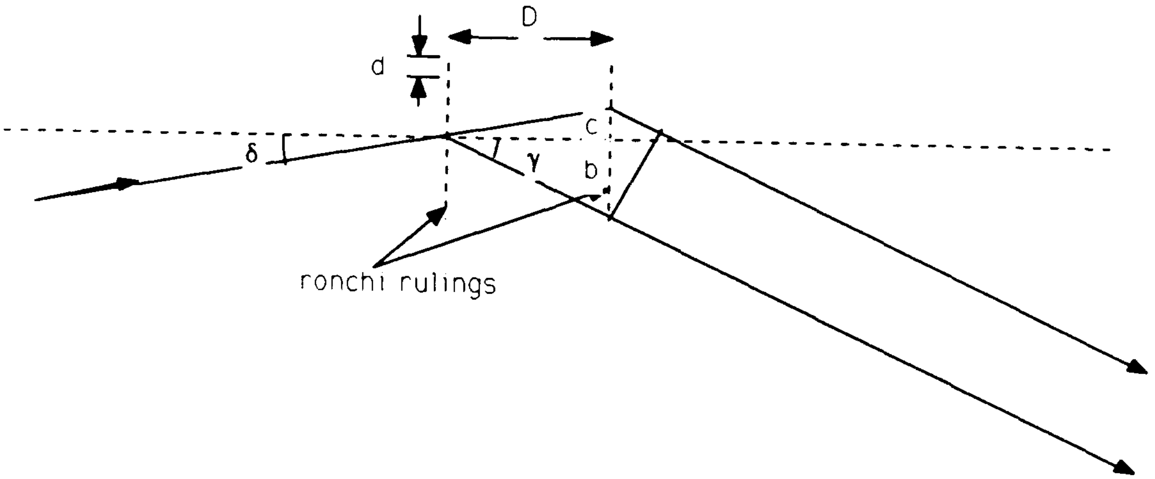

Figure 8: Moiré-Schlieren fringe conditions.