Display

CLM-P 265

United Kingdom Atomic Energy Authority
RESEARCH GROUP

Preprint

NANOSECOND LASER PULSE GENERATION USING AN ELECTRO-OPTIC SHUTTER EXTERNAL TO THE Q-SPOILED CAVITY

P. D. MORGAN
N. J. PEACOCK

Culham Laboratory
Abingdon Berkshire

1971

CLM-P 265

NANOSECOND LASER PULSE GENERATION USING AN ELECTRO-OPTIC SHUTTER EXTERNAL TO THE Q-SPOILED CAVITY

by
P.D. Morgan[†]
N.J. Peacock

(Submitted for publication in J. Phys. E, Scientific Instruments)

ABSTRACT

An electo-optic switching circuit is described which will produce a pulse of one nanosecond duration or less from a ruby laser. The switch, external to the Q-spoiled oscillator cavity, uses a KD*P Pockels cell which is driven by a full-wave voltage pulse. The laser pulse, after × 15 amplification, has an energy of 3×10^{-2} joules and is sufficiently coherent and free of jitter to find a ready application in the diagnostics of highly transient plasmas.

[†] Royal Holloway College

U.K.A.E.A. Research Group,
Culham Laboratory,
Abingdon, Berks.

February, 1971.

1. INTRODUCTION

The problem of producing a laser pulse of duration 1 nanosecond or less is of importance in diagnostic measurements of transient high-density plasmas produced, for example, in the Plasma Focus device (Peacock et al. 1969), or by irradiation of solid targets by high-powered lasers (Basov et al. 1968). The speed of the density fronts in these plasmas can be up to 0.4 mm/nanosecond while the characteristic dimensions of the structure in the plasma are often $\lesssim 0.1$ mm. For diagnostic purposes, e.g. refractive index measurements, pulses of high energy are not necessary, $\lesssim 0.01$ J being adequate for single pulse illumination of the plasma, though for multiple exposure sequences (Basov et al. 1967) at least this energy per pulse is desirable. It is advantageous when making holographic or interferometric studies to have a coherence length of several cm and a beam divergence of a few milliradians. It is also desirable to have the pulse to pulse jitter considerably less than 10 nsec so as to be able to illuminate the plasma at the same time during its formation or decay on successive discharges.

Because of the fine-grained spatial structure of these transient phases it is not very practicable to illuminate the plasma with a long (~ 50 nsec) laser pulse and shutter the exposure using recent developments in image converter cameras, (Bradley et al. 1970). It is desirable therefore to employ laser pulses which have the required time resolution or shorter, i.e. $\lesssim 1$ nsec.

There are two well-tried methods of producing pulses of shorter duration than those yielded by conventionally-switched Q-spoiled lasers, viz. the pulse-transmission mode laser (Hook et al. 1966) and the mode-locked laser (see for example DeMaria et al. 1966). The duration of a light pulse produced by the first method is determined by the time required for light to travel twice the path between the reflectors of the oscillator cavity. In order to produce a pulse duration of 500-700 picosec the overall oscillator cavity length has to be less than 7.5 cm and the switching of the electro-optic cell in the cavity has to be accomplished in ~ 200 picosec. These requirements are difficult to meet. The mode-locked oscillator on the other hand lacks the coherence which is convenient for interferometric diagnostics. In order to produce clean, mode-locked pulses a saturable dye switch within the cavity is necessary, and the overall jitter between the start of the flash-tube discharge and the appearance of the output pulse is typically several microseconds.

The present paper describes the results of pulse-clipping the output pulse from a conventionally Q-switched cavity. This technique gives a pulse which fulfills all the requirements for the optical study of highly-transient plasmas.

2. THE EXPERIMENTAL METHOD

The use of an extra-cavity electro-optic shutter to shorten the output of a Q-switched laser is perhaps an obvious technique, but it has been employed only recently (see for example Michon et al. 1969 and Alcock and Richardson 1970). In these references, the electro-optic shutter was switched from zero voltage corresponding to the condition for blocking the polarised oscillator beam, to $V_{\lambda/2}$ (the half-wave voltage) corresponding to full transmission, and then back to zero voltage. The half width of the voltage pulse then determined the laser pulse-width.

In the present arrangement, shown schematically in Figure 1, the electro-optic shutter external to the cavity is a KD*P cell, which requires a relatively modest voltage, approximately 5 kV, to rotate the plane of polarisation through 90° (the half-wave voltage). A laser-triggered spark gap (LTSG) similar to that described by Bradley et al. (1969) is used to generate the voltage pulse on the KD*P cell. Maximum energy in the transmitted pulse is gained by clipping the oscillator output at its peak intensity using a Blumlein circuit, Figure 1. Full-wave switching is employed. This means that transmission of the output from the ruby oscillator is allowed only over that part of the steep falling edge of the voltage pulse centred around the voltage $-V_{\lambda/2}$ as illustrated in Figure 1. For identical circuit parameters, e.g. switching voltage, spark gap impedance, Pockels cell impedance and coaxial cable characteristics, full-wave switching in this manner can yield shorter laser pulses than those reported previously.

3. MODE OF OPERATION

The Korad K-1500 ruby laser system used for the short pulse generation is basically a conventionally Q-switched oscillator and an amplifier giving typically 10 joules in a pulse whose half width is ~ 17 nanoseconds. When Q-switched the plane polarised output from the oscillator passes through the unbiased KD*P Pockels cell with no rotation of the plane of polarisation. The Pockels cell is operated in the longitudinal mode and has an aperture of 1 cm. A Glan-Thompson polariser prevents transmission through to the amplifier and deflects the beam onto the LTSG.

The LTSG consists of two brass electrodes 100 μ apart and open to the atmosphere with a Melinex sheet of thickness 50 μ separating the electrodes. A static voltage of about 14 kV is maintained across the gap. Triggering is achieved by puncturing the dielectric with the laser beam which is focussed with a 5 cm focal length lens onto one electrode through a 1 mm hole in the other. The Melinex sheet is replaced after each shot. The LTSG is capable of switching voltages of $\sim$ 15 kV with nanosecond risetime and jitter. The delay in the gap breakdown is the order of a few nanoseconds and depends on the incident laser power. With the present arrangement the threshold for breakdown occurs at a power level of $\sim$ 1 MW.

One electrode of the LTSG is connected to the inner conductor at one end of the Blumlein cable (Wilkinson 1946), of half-length L, while the other electrode is connected to the outer conductor at the same end of the cable. Uniradio 67 cable is used with a characteristic impedance, Z_0, of 50 Ω. The inner conductor of the Blumlein cable is charged to a voltage $+ V_\lambda$, the outer conductor being earthed. The outer conductor has a short break in it at the midpoint of the Blumlein, and the load which is the Pockels cell in parallel with a $2Z_0$ resistance is connected across the break to the two sections of conductor. The other end of the Blumlein cable is an open circuit.

When the LTSG is triggered, at time t_t (Figure 1), a voltage step of magnitude $- V_\lambda$ is launched into the cable in the direction of the load. At a time $\frac{L}{v}$ after the gap breakdown (v denotes the velocity of propagation in the cable), a rectangular pulse of magnitude $- V_\lambda$ and duration $\frac{2L}{v}$ appears across the load. As the voltage across the Pockels cell decreases from zero to $- V_\lambda$ volts, during the leading edge of the pulse, so the plane of polarisation of the laser light passing through the cell is rotated through a full 180°. The degree of rotation is proportional to the applied voltage. Thus, at a given voltage level, $- V_{\lambda/2}$, on the leading edge of the pulse, the plane of polarisation at the output of the Pockels cell will have rotated through 90^0. The oscillator light can now pass straight through the Glan-Thompson polariser into the amplifier. However, the applied voltage continues to fall to $-V_\lambda$, corresponding to 180^0 of rotation, where again the oscillator output is rejected sideways at the Glan polariser interface. The duration of the rectangular clipping pulse, $2L/v$, is sufficiency long to block the remainder of the Q-spoiled pulse. Thus, the shutter only admits light through to the amplifer over a portion of the leading edge of the applied electrical pulse, centered around the point where the voltage is $-V_{\lambda/2}$, (Figure 1). By adjusting the flux of light on the LTSG and choosing a suitable length for the Blumlein cable, the time at which the voltage pulse arrives at the KD*P Pockels cell is arranged to coincide with the maximum of the Q-spoiled pulse $(t = t_p)$. The shuttered pulse which is admitted to the amplifier is thus of maximum intensity. Because of mismatching and losses in the cable, the static voltage on the Blumlein has to be somewhat greater than the pulsed full-wave voltage of the Pockels cell. Also, because of losses within the Pockels cell, the applied pulse voltage is ~ 1 kV higher than the calculated pulsed full-wave voltage (10·4 kV).

4. RESULTS AND DISCUSSION

Figure 2 shows the waveform of the electrical pulse appearing across the Pockels cell. The pulse is monitored using a low-inductance resistive voltage divider coupled to a Tektronix 519 oscilloscope, the inherent risetime of the measuring system being 0·9 nanoseconds. The risetime between 10% and 90% of peak amplitude is 2·5 nanoseconds. This is approximately equal to 2·2 τ where τ is the 1/e time.

Figure 3 shows the waveform of the amplified optical pulse monitored using an ITL (HCBI) photodiode which with a 519 oscilloscope has an inherent rise time of 0·35 nsecs. The duration of the optical pulse (HPFW) is 1·2 nsecs.

For an electro-optic cell operating in the longitudinal mode and mounted between crossed polarises as in Figure 1, the transmission I, can be expressed as a function of the modulation voltage ratio $V/V_{\lambda/2}$, i.e.

$$I_v/I_i = \sin^2(\pi/2 \frac{V}{V_{\lambda/2}}) \qquad \ldots (1)$$

where I_i is the incident light flux. For any voltage step the half-intensity points of the Pockels cell transmission correspond to 25% and 75% of the full amplitude of the switching voltage, $- V_\lambda$, as given by equation (1). The time between these voltage levels is $\sim 1{\cdot}2\ \tau$, as shown in Figure 4(a). The measured optical pulse width, Figure 3, is 1·2 nanoseconds and is in good agreement with this value. The rise time of the optical pulse is 0·8 nanoseconds.

The fall time of the leading edge of the electrical pulse at the Pockels cell can be considered as the product of two exponentially decreasing voltages with characteristic times τ_1 and τ_2, where τ_1, the fall time due to the switch inductance L_s, is L_s/Z_0, and τ_2, the fall time due to the Pockels cell capacitance C, is $2CZ_0$. With full-wave switching using a Blumlein circuit it can be shown that in general the open time of the electro-optic switch varies from $1{\cdot}1\ \tau$ ($\tau = \tau_1 \gg \tau_2$ or $\tau = \tau_2 \gg \tau_1$) to $1{\cdot}3\ \tau$ ($\tau_1 = \tau_2 = \tau$); see Figure 4(a).

Similarly the half-wave switching procedure (see for example Alcock and Richardson 1970), using a different circuit configuration, can be shown to give transmission, reaching full intensity, for approximately $1{\cdot}5\ \tau$ to $1{\cdot}8\ \tau$, Figure 4(b).

Some improvement in narrowing the pulse can be achieved; (a) by reducing the aperture (and hence capacitance) of the Pockels cell;

(b) by using several cables in parallel in the Blumlein, $Z_{eff} = Z_0/N$, and (c) by reducing the inductance of the LTSG. No special attempts were made to do so in the work described in this paper and, for example, a standard Pockels cell of aperture 1 cm was used. Taking the above simple precautions, however, it should be possible to produce a voltage pulse with a rise time of $\sim$ 1 nanosec across the Pockels cell and thus obtain an optical pulse of $\sim$ 500 picosec duration.

After amplification ($\times$ 15) and passage through a cryptocyanine cell to improve the peak to background contrast, the energy in the shuttered pulse is 3×10^{-2} joules which is sufficient for many diagnostic purposes in plasma physics. The divergence of the clipped laser pulse was not measurably greater than that of the conventional Q-spoiled pulse, i.e. 3 milliradians contained 90% of the beam energy.

A lower limit to the spectral width of the laser beam, $\frac{\lambda^2}{c\Delta t}$, is set by the duration of the clipped pulse, Δt. In the present experiments, with $\Delta t = 1{\cdot}2$ nanosec, a monochromatic continuous laser beam would be broadened to 0·013 Å. However, mode coupling in the oscillator cavity did not, in practice, allow line widths of less than 0·075 Å so that no appreciable deterioration in line width, and therefore in coherence length, was introduced by the pulse clipping. A Fabry-Perot interferogram of the amplified pulse, taken with an etalon spacing of 1·0 cm, is shown in Figure 5. The line width, 0·075 Å, corresponds to a coherence length of 3·2 cm, which is sufficiently long for nanosecond-exposure interferometry.

A 10 nanosecond exposure photograph of the visible light from the dense Plasma Focus (Peacock et al. 1969) using an image-converter camera is shown in Figure 6(a). For comparison, a 1 nanosecond exposure shadowgraph of the same plasma using the ruby laser source with full-wave switching is shown in Figure 6(b). It is readily appreciated that without the required spatial and temporal resolution many of the features of the plasma are overlaid and lost. Along the axis of symmetry of the device the shadowgraph shows that there is a density gradient structure which has characteristic radial dimensions less than 0·1 mm. The boundary of the plasma is also sharp and is scalloped by Rayleigh-Taylor instabilities. Multiple-exposure shadowgrams show that these features change in their spatial positions in times considerably less than 10 nanoseconds. High spatial resolution, > 100ℓ/mm, and nanosecond exposure is therefore necessary to study the growth rate of the instabilities and to identify the source of the axial structure.

5. CONCLUSIONS

An electro-optic shutter has been developed which is capable of giving nanosecond pulses from a ruby laser. The method used involves full-wave switching of a KD*P Pockels cell external to the oscillator cavity. The laser, with a × 15 amplifier, has adequate energy, 30 millijoules, coherence length, 3·2 cm, and time resolution, 1 nsec, to find immediate application in the diagnostics of dense, highly-transient plasmas. It may also prove useful as a first stage of a multi-stage laser system for creating high temperature plasmas from a solid target when irradiated by the focussed laser beam.

ACKNOWLEDGEMENTS

The authors would like to thank P D Wilcock for many helpful discussions on this problem.

REFERENCES

ALCOCK, A J and RICHARDSON, M C, (1970), Optics Communications, 2, (2), 65-68.

BASOV, N G, KROKHIN, O N and SKLIZKOV, G V, (1967), Applied Optics, 6, (11), 1814-1817.

BASOV, N G, KROKHIN, O N and SKLIZKOV, G V, (1968), Jnl. Quant. Electronics, 4, (12), 988-991.

BRADLEY, D J, HIGGINS, J F, KEY, M H and MAJUMDAR, S, (1969), Opto-Electronics, 1, (1), 62-64.

BRADLEY, D J, HIGGINS, J F and KEY, M H, (1970), App. Phys. Letters, 16, (2), 53-55.

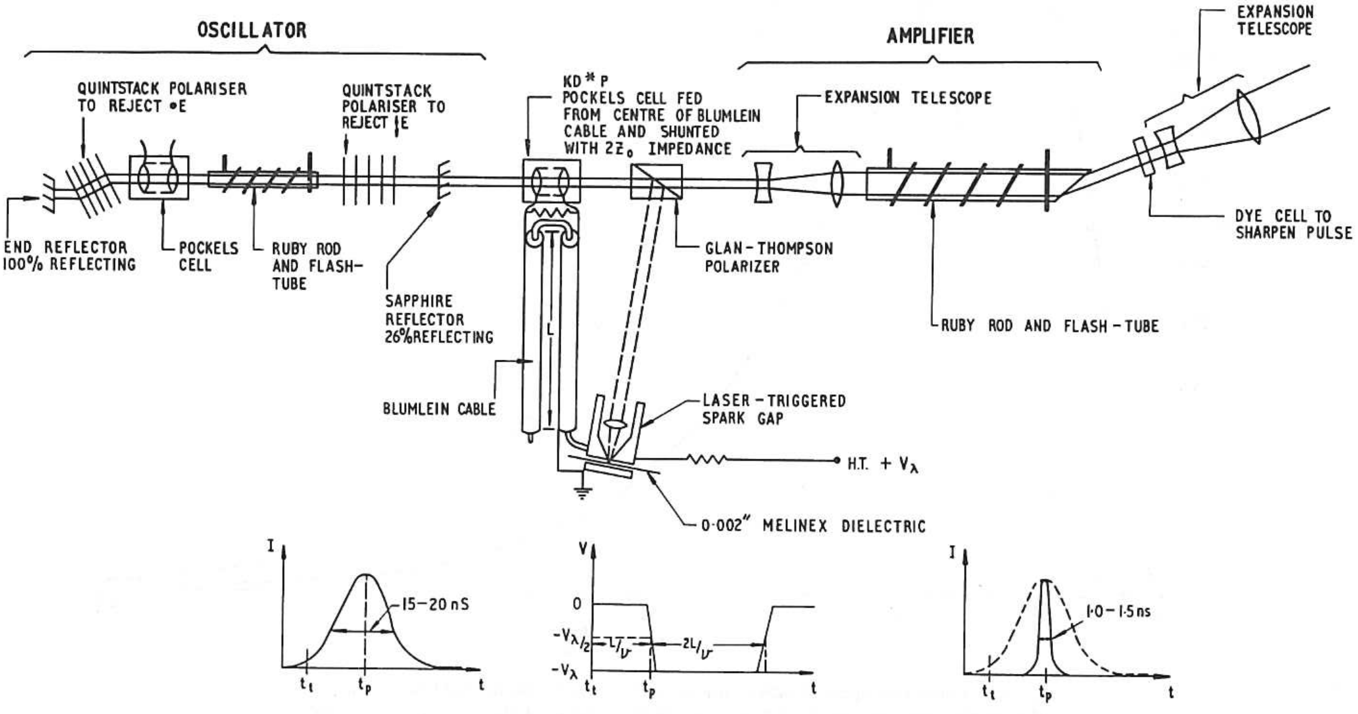
DeMARIA, A J, STETSER, D A and HEYNAU, H, (1966), App. Phys. Letters, 8, (7), 174-176.

HOOK, W R, DISHINGTON, R H and HILBERG, R P, (1966), App. Phys. Letters, 9, (3), 125-127.

MICHON, M, GUILLET, H, Le GOFF, D and RAYNAUD, S, (1969), Rev. Sc. Inst., 40, (2), 263-265.

PEACOCK, N J, WILCOCK, P D, SPEER, R J and MORGAN, P D, (1969), Proceedings of the 3rd Int. Conference on Plasma Physics and Controlled Nuclear Fusion Research, Novosibirsk, Aug. 1968. (IAEA, Vienna, 1969). Vol.II, pp.51-65.

WILKINSON, K J R, (1946), J. Inst. E.E., 93, pt.IIIA, (6), 1090-1112.



OUTPUT FROM OSCILLATOR •E

ELECTRICAL WAVEFORM ACROSS KD*P POCKELS CELL

INPUT TO AMPLIFIER ↕E

Fig.1 Schematic diagram of nanosecond optical pulse generator.

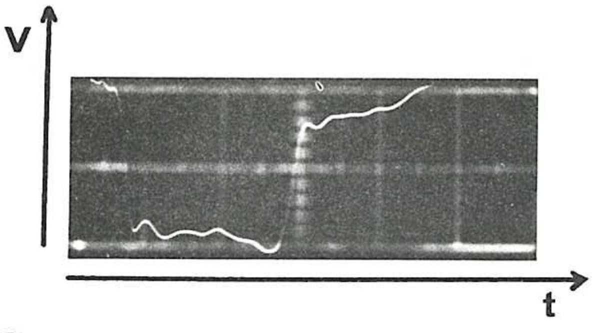


Fig.2 Waveform of electrical pulse across Pockels cell. Horizontal scale 10 nsec/major division. Vertical scale 5·7 kV/major division.

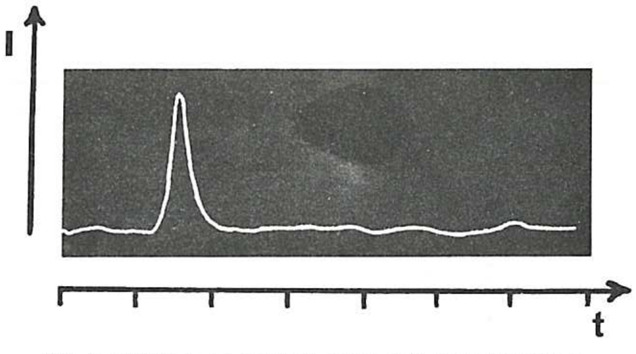


Fig.3 Waveform of optical pulse after amplification (retouched for clarity). Time scale 5 nsec/division.

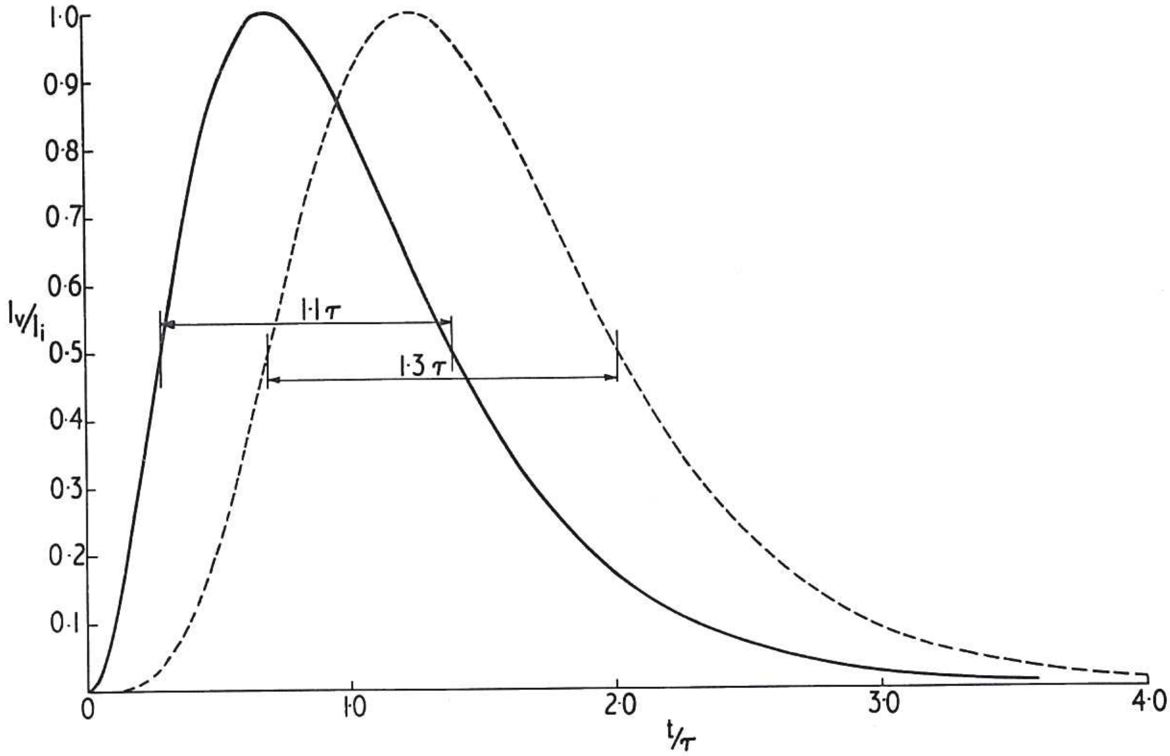


Fig.4(a) Computed optical waveform of pulse produced by full-wave clipping. (Full curve denotes $\tau_1 \gg$ or $\ll \tau_2$; broken curve denotes $\tau_1 = \tau_2$; for definition of τ_1 and $\tau_2{}'$ - see text).

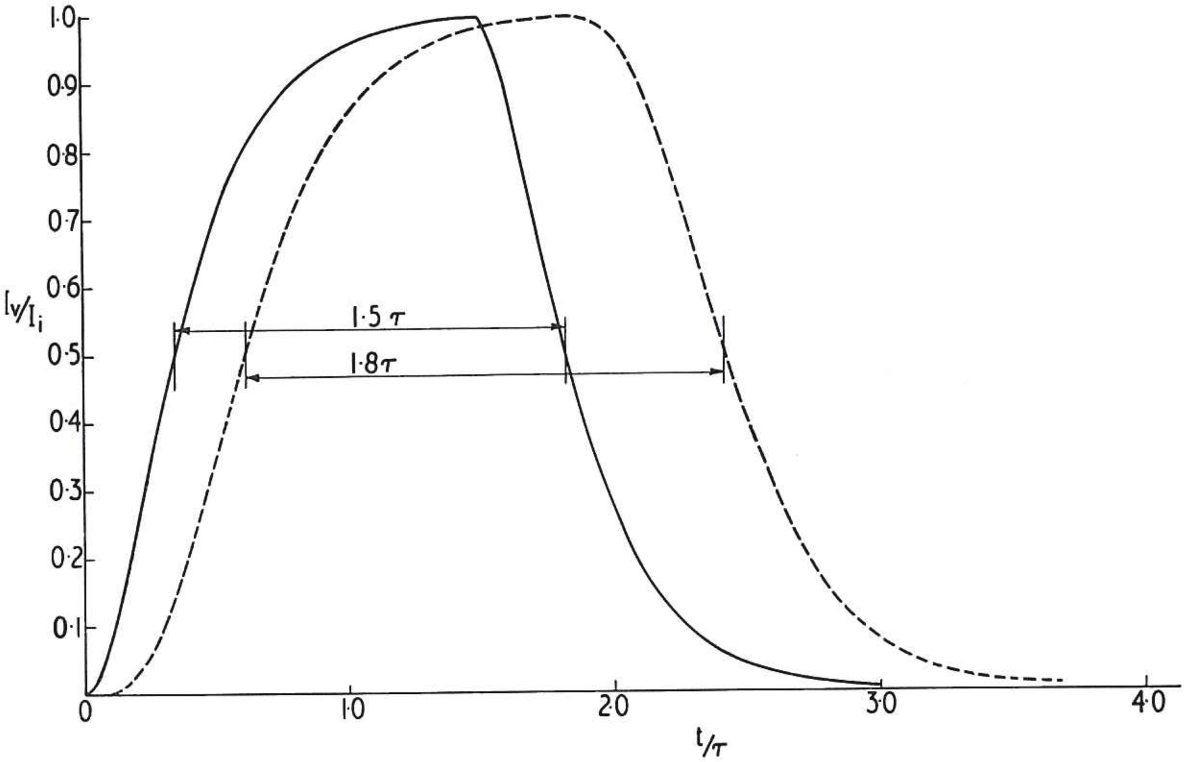


Fig.4(b) Computed optical waveform of pulse produced by half-wave clipping. (Full curve denotes $\tau_1 \gg$ or $\ll \tau_2$; broken curve denotes $\tau_1 = \tau_2$; for definition of τ_1 and τ_2 - see text).

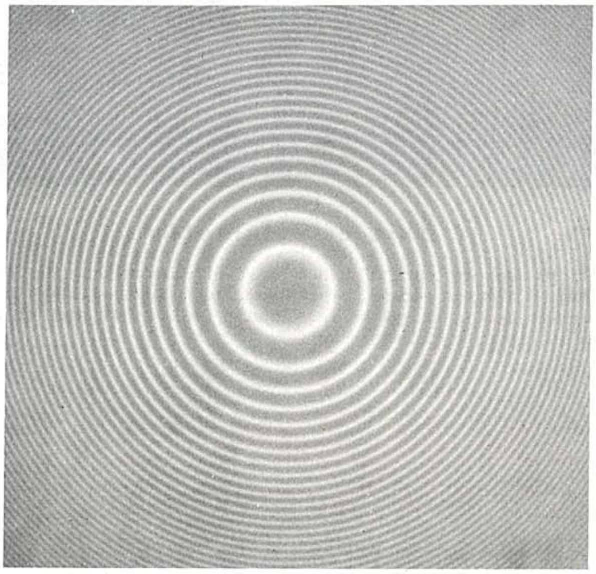


Fig.5 Fabry-Perot interferogram of light in amplified clipped pulse. Free spectral range 0·24 Å.

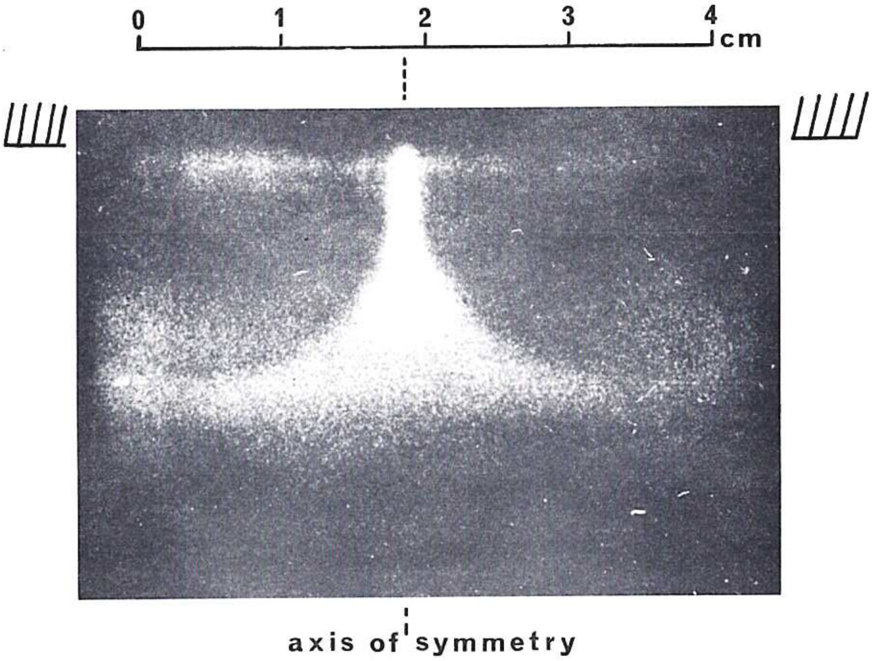


Fig.6(a) 10 nsec exposure of pinch stage of Plasma Focus device taken with image converter camera. The plasma is compressed into the form of a fountain by the axisymmetric magnetic field. The stem of the fountain is close to the anode surface.

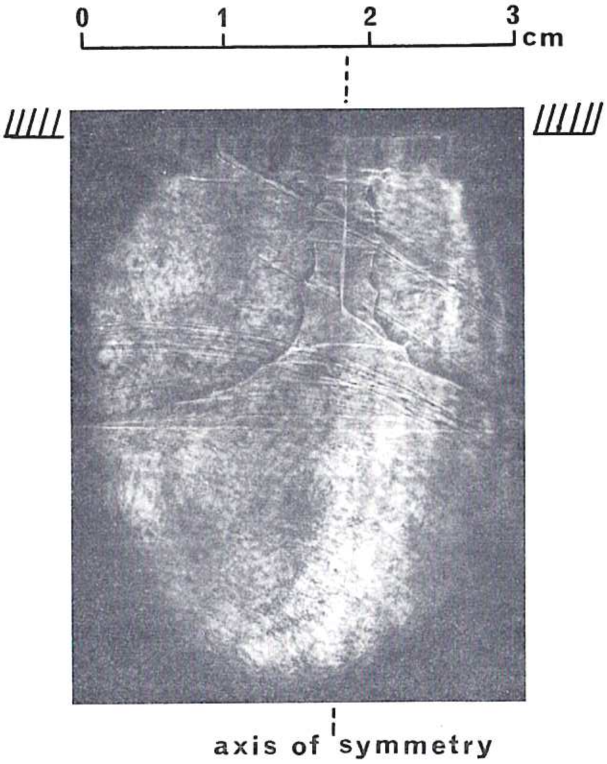


Fig.6(b) Shadowgram of pinch stage of Plasma Focus device using amplified clipped pulse for illumination. The diagonal striations across the field are spurious and are due to non-uniformity of the illuminating laser beam.