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Development of picosecond time resolution optical and X-ray streak cameras

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Abstract. We describe the development of an optical and an X-ray streak camera with picosecond time resolution. The entire peripheral electronics and testing systems have been developed indigenously. Both the streak cameras provide ~ 15 mm/1 ns streak rate with a sweep voltage of ~ 1 kV amplitude and rise time of 1 ns. The time and spatial resolution of the optical streak camera have been found to be ~ 17 ps and 100 μm respectively. The sweep pulse generator developed for this purpose provides a step pulse of rise time $\leqslant 1$ ns and amplitude ~ 2 kV. The laser diode used for testing the optical streak camera provides multiple pulsation when the pump current is increased beyond a critical threshold.

Keywords. Optical and X-ray streak cameras; picosecond time resolution; multiple pulsation.

1. Introduction

A streak camera is one of the most versatile instruments (Schelev *et al* 1972; Bradley *et al* 1980; Campillo & Shapiro 1983; Kinoshita *et al* 1983; Stradling *et al* 1983; Tsuchiya 1983; Dashevsky *et al* 1988) used today for high speed photometry in the field of physics, chemistry, biology and nonlinear optics. Conventional optical detectors such as biplanar photodiode and PIN silicon photodiode used with the fastest available oscilloscope provide a time resolution of 10^{-10} s. Various other techniques generally used for investigating very fast events are the autocorrelation method, second harmonic generation, two-photon fluorescence and four-photon parametric mixing. However, certain amount of errors (inaccuracies) are always associated with these measurements. Amongst all the available methods, streak photography is considered to be the best for recording ultrafast optical phenomenon with an excellent time resolution (< 1 ps). It can provide a temporal profile of any optical event directly even in a single-shot operation. In addition to the time duration, rise time as well as shape of the optical pulse also can be recorded along with intensity modulation (fine structure) if present, during the optical event. However, measurements will be limited by the time resolution of the streak camera. Streak cameras with nanosecond time resolution were built long ago, but temporal resolutions of the order of picoseconds or sub-picoseconds has been achieved only a few years ago. A new streak camera with femtosecond time resolution has also been reported (Kinoshita *et al* 1987). Highly sensitive streak cameras with picosecond time resolution are now commercially available which are capable of recording any phenomenon in the spectral range extending from near infrared to ultraviolet and soft X-ray (100 eV–10 keV) regions with the help of suitable photocathode attachment (Schelev *et al* 1972; Bradley *et al* 1980; Campillo & Shapiro 1983; Kinoshita *et al* 1983; Stradling *et al* 1983; Tsuchiya 1983; Dashevsky *et al* 1988). In fact, the streak camera can functionally be referred to as a >300 GHz band width optical oscillosocope. However, the streak camera possesses many more special features and scores over an ordinary oscilloscope, for example, it can provide three-dimensional information such as spatially time-resolved as well as time-resolved spectroscopic intensity profiles (Campillo & Shapiro 1983; Tsuchiya 1983). Either a photographic system or a digital image memory is used to store and analyse three-dimensional streak images. The latter provides almost real-time measurements of the events.

The present paper reports on the development of a picosecond resolution optical (Rai *et al* 1994b) and X-ray streak cameras (Rai *et al* 1994c) intended for studying fast processes in IR, visible, UV and soft X-ray wavelength regions. The design of the instrument, its peripheral electronics, radiation sources for testing the cameras as well as test results are presented. Section 2 describes both types of streak tubes used in these experiments. Section 3 reports the development of related electronics to drive the streak camera. Section 4 provides information about various kinds of optical sources used for testing the streak cameras. Test results and discussions are presented in § 5, whereas conclusions are given in § 6.

2. Streak tubes

2.1 *Optical streak tube*

We have used the optical streak and image intensifier tubes manufactured by General Physics Institute, Moscow for building our optical streak camera (figure 1). It has an S1 type photo cathode (Ag–O–Cs) deposited on a flat glass plate of 5 mm diameter and is sensitive in the spectral range 450–1150 nm with peak response at 800 nm. An accelerating grid placed at distance of 1 mm from the photocathode has 60% transmission. The grid is used for gating as well as for reducing the time resolution limit of the tube to $\leqslant 1$ ps. The tube has a focussing electrode which focusses the photo electrons on to the phosphor screen and also decides the spatial resolution of the tube. The photo cathode, accelerating grid and focussing electrodes require biasing voltages of -15, -13 and -12 to -13 kV respectively. It has an anode which acts as an aperture in the tube and remains at the ground potential. There are two pairs of deflector plates out of which one pair is used to sweep the photo electrons on the screen whereas the other pair is used to fly back the photo electrons to the initial position without streaking back on the screen to the position from where sweeping started. The phosphor screen of the camera is made of aluminized P11 material which has peak response at 460 nm (blue region) and is coupled to the output face of an optical fibre plate. The tube is of the sealed-off type with a glass window on the photocathode side. An image intensifier tube

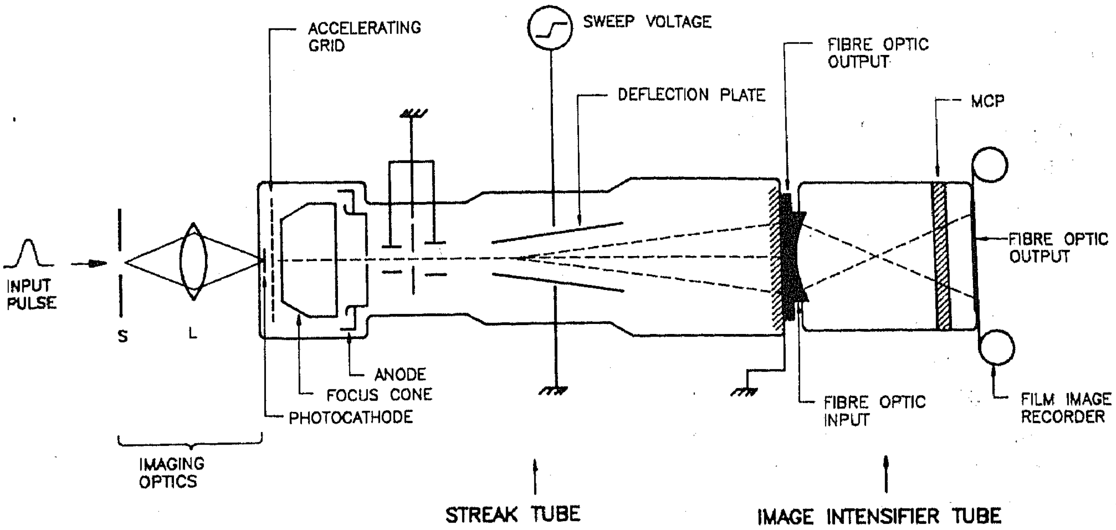


Figure 1. Schematic diagram of streak camera.

is coupled to the streak tube as shown in figure 1. The image intensifier tube consists of a photocathode, a phosphor screen and a multichannel plate (MCP) to multiply the photoelectrons. This system is used to enhance the intensity of the image obtained at the phosphor screen of the streak tube. It has a maximum gain of $\sim 10^4$ divided into 5 steps. Finally, the image on the screen of the intensifier is recorded by using a contact photograph or a charge coupled device (CCD) camera.

2.2 *X-ray streak tube*

The input end of the X-ray streak tube (also obtained from the Institute of General Physics, Moscow) is attached to a metallic flange, which has a clearance for the photocathode at the centre and a number of small holes around it to evacuate the tube. Generally, an X-ray streak tube has a demountable photocathode and is evacuated directly during experiments. The rest of the parts of the tube are similar to that of optical streak tube. The X-ray sensitive photocathode consists of a 300 Å thick gold film deposited on a 1000 Å thick parylene or nitrocellulose film which is fixed on the cathode disc having a $100\,\mu$m $\times$ 9 mm slit. This photocathode is sensitive to soft X-rays ranging from 100 eV to 10 keV as well as to UV radiation. The slit image produced by the incident soft X-rays is focussed on to the phosphor screen by the electron lens made by the combination of accelerating mesh, the focussing electrode and the anode. The photoelectrons are streaked on the 40 mm diameter screen by means of the vertical deflection electrodes. The intensity of the image is then enhanced by the image intensifier tube and the output image is recorded using a camera.

3. Electronics

The peripheral electronics of the streak camera contain various kinds of fast and high- as well as low-voltage pulser circuits. The main high voltage pulse requirements for the operation of streak camera are (i) a high voltage (~ 1 kV) linear ramp of dual polarity for full deflection of the image across a 25 mm image intensifier screen, (ii) a short rectangular pulse of variable time duration (100 ns – 2 μs) and amplitude (max 2 kV) to gate the accelerating grid as well as to increase the time resolution of the camera, (iii) a trigger pulse generator, which triggers the sweep circuit. This generator is externally triggered by a fast photo diode signal, (iv) high voltage DC power supplies to bias various electrodes of streak and intensifier tubes such as photocathode, accelerating grid and focus electrode as well as to drive the sweep and gate pulse circuits.

3.1 *Sweep pulse circuit*

A picosecond time resolution is obtained in a streak camera by streaking the photoelectrons with a streak velocity ~ 10^{10} cm/s. This indicates the requirement of a sweep voltage having a rise time ⩽ 1 ns. Rise time obtained using an RLC integrated circuit is slower than this requirement. In order to prevent image distortion and improve camera dynamics as well as spatial resolution, two symmetrical well-balanced sweep pulses are required which in fact makes the sweep pulse faster in comparison to the single sweep of same rise time. The nonlinearity in the sweep pulse and, as a result, the sweep speed are improved by increasing the amplitude of the sweep pulse beyond the required value (overpulsing). Many circuits have been reported for generating a sweep pulse for the streak camera. These utilize various kinds of fast switching elements such as krytron (Bradley *et al* 1972), power-beam microwave triode (Alcock *et al* 1970), laser triggered spark gap (Alcock *et al* 1970; Schelev *et al* 1972) as well as avalanche transistors (Cunin *et al* 1980; Baker 1991). The transistorized circuits available to date provide rise times of 1·5 to 2 ns depending on whether avalanche transistors are used in a series stack mode or in a Marx bank configuration. Two pulser circuits (Rai *et al* 1994a; Rai & Shukla 1994) were developed in our laboratory. One of the pulser circuits was developed (Rai & Shukla 1994) by using a stack of 15 avalanche transistors, 2 N 5551, connected in series as a single switching element which is shown in figure 2. A transmission line of 75(50) Ω impedance and ~ 1·5 m in length was charged to 4·5 kV and discharged through a 75(50) Ω load. We obtained a square step pulse of ~ 2 kV across a 75 (50) Ω resistor instead of ~ 2·25 kV as a result of a small voltage drop across the

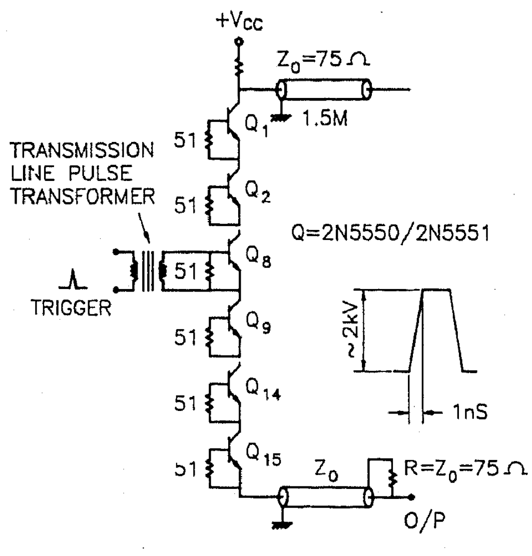


Figure 2. Diagram of sweep pulse generator circuit.

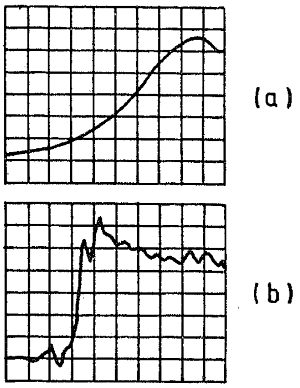


Figure 3. Oscillograms of sweep pulses recorded on a Tektronix model 7104 oscilloscope (1 GHz) having vertical plug in model 7A29. (**a**) Horizontal – 200 ps/div., vertical – 400 V/div.; (**b**) horizontal – 2 ns/div., vertical – 400 V/div.

transistors due to its finite resistance during the breakdown. This circuit provides a square pulse of rise time 800 ps (10–90%) as shown in figure 3 when recorded on a Tektronix oscilloscope (model 7104) having a vertical plug in model 7A 29 which had a combined bandwidth of 1 GHz. To achieve rise times better than 1 ns, with a series combination of transistors; reduction in excess leads and proper soldering are needed to reduce the extra inductance in the circuit. A carefully designed printed circuit board was prepared for this purpose. This circuit was triggered through a wide band pulse transformer which consists of a small toroidal ferrite core with five turns of 50 Ω coaxial cable, where the cable shield acts as a primary and the central conductor as a secondary. Triggering of any transistor in the stack switches the circuit, but better stability was obtained when a middle transistor of the stack was triggered. Triggering pulse was sharpened using a 20 PF capacitor and 50 Ω resistance at the output of the transmission line pulse transformer in a differentiation mode. Small pulse width of the trigger pulse effectively protects the base emitter junction of the transistor being triggered and as a result enhances the life time of the circuit. Many earlier reported circuits (Cunin *et al* 1980; Baker 1991) use a ballast resistance between emitter and collector of each transitor to avoid self-triggering in the circuits. We, however did not observe any self-triggering in our circuits even without the ballast resistances. Nevertheless, a properly designed ballast circuit may decrease the high jitter (< 500 ps) observed in this case to < 100 ps and may keep the string from self-triggering over a wide temperature range.

A simple technique was used for generating two symmetrically opposite polarity pulses from a single pulse of either polarity. This arrangement is shown in figure 4 which had two similar length (2 m) 75(50) Ω impedance cables connected in parallel at the output of the pulser circuit and terminated with 75(50) Ω resistances. Towards the

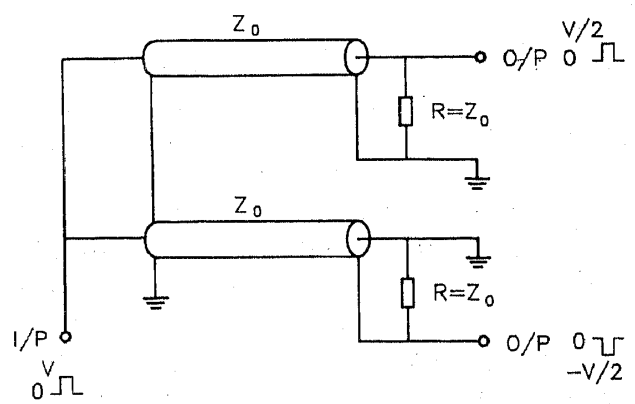


Figure 4. Arrangement to obtain positive and negative polarity pulses from a pulse of either polarity.

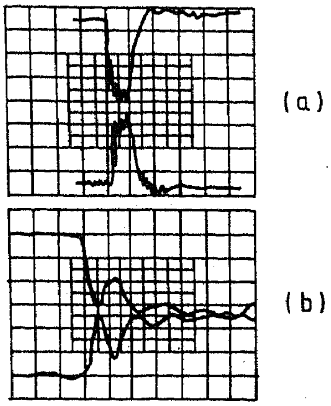


Figure 5. Oscillograms of two opposite polarity pulses recorded on a Tektronix model 7348 oscilloscope (400 MHz) having vertical plug in model 7A19. (**a**) 10 ns/small div., vertical – 160 V/small div.; (**b**) 1 ns/small div., vertical – 160 V/small div.

termination end, the first cable was grounded at the shield and the output was taken from the central pin which provided a similar polarity pulse, like an input pulse but around one half in amplitude. The second cable has its central pin grounded at the termination end and the output was taken from the shield of the cable (figure 4) which provided an opposite polarity pulse in comparison to the input pulse and similar in amplitude as was obtained from the first cable. Care must be taken to isolate the shield of the latter cable with the normal ground at the termination end, otherwise the rising edge of the pulse becomes distorted. Figure 5 shows the two symmetrically opposite polarity pulses of rise time better than 1 ns. In the case of application of these pulses in the streak camera only the rise time, amplitude and a small delay are important parameters of the pulser circuit. These opposite polarity pulses were used to operate the streak camera. However, it was noticed that the rise time of the pulse was modified to $\sim 2{\cdot}5$ ns due to capacitive loading from the deflection plate. The superimposed fluctuations observed on the pulses in figures 3 and 5 appear to be due to the unwanted signals travelling on the outside of the outer conductor. These fluctuations can be removed or minimised by placing the circuit in a properly shielded box or by wrapping the coaxial cable on a large ferrite core. The signal on the outside of the outer conductor will travel at a slower velocity due to the high μ value of the ferrite. For the slow streak velocity, an RLC integrator was used at the output of the circuit.

3.2 *Gate pulse circuit*

It has been reported earlier (Schelev *et al* 1972) that the resolution of the streak camera strongly depends on the electric field between photocathode and grid. Normally 1–2 kV is sufficient but for better time resolution a higher voltage is required on the grid beyond the normal value, which is provided in the form of a pulse to avoid undesirable effects (Schelev *et al* 1972). Sometimes a gating is needed to avoid the background noise also. For this purpose, a gate pulse of positive polarity is required, having amplitude 1–2 kV and time duration ~ 100 ns, much higher than the sweep voltage time (~ 1–20 ns) but synchronized with it. A pulse of this time duration (100 ns) can be obtained by using the earlier circuit (figure 2) with at least ~ 10 m length of a coaxial cable of 50 Ω impedance. To simplify this circuit the coaxial cable was replaced by a discrete element transmission line. The impedance of this transmission line was increased to 1000 Ω to decrease the current flowing in the circuit to avoid the failure of transistors as was observed in the case of a 50 Ω impedance line providing $\geqslant 100$ ns time duration pulses.

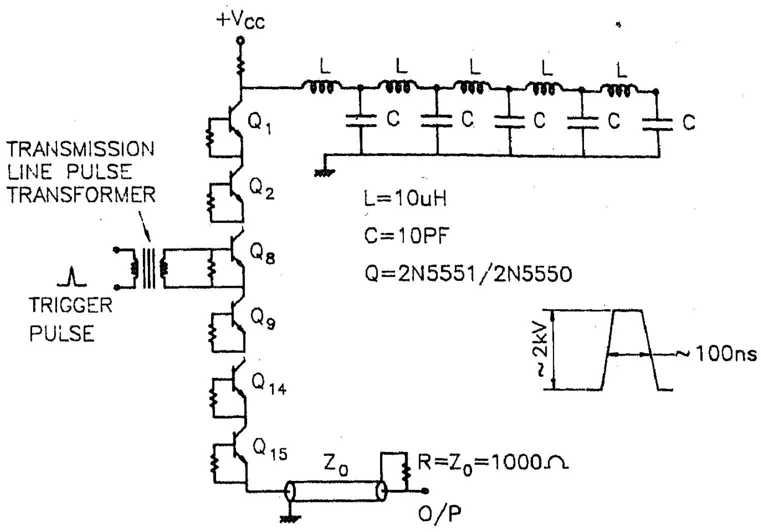


Figure 6. Diagram of gate pulse circuit.

The gate pulse circuit is shown in figure 6 which provides a square pulse of ~ 100 ns duration with 1·5 kV amplitude. This line also acts as a low pass filter for all the frequencies between zero and $(2\pi(LC)^{1/2})^{-1}$ whereas the impedance of the line is given by

$$R_L = (L/C)^{1/2}. \tag{1}$$

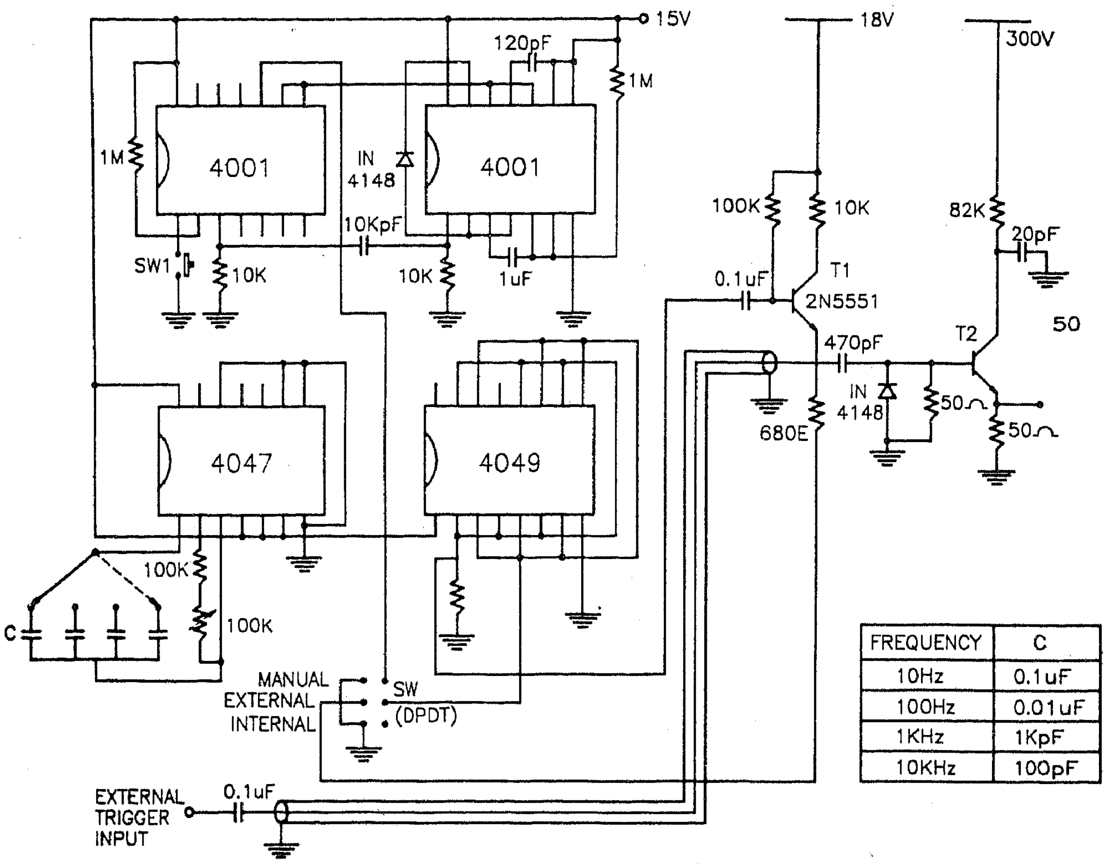
The quantity $(LC)^{1/2}$ represents the delay time per section of the line (low pass filter). Therefore, an n-section filter will produce a pulse of duration τ given by,

$$\tau = 2n(LC)^{1/2}. \tag{2}$$

The values of $L = 10\,\mu$H and $C = 10$ pF was calculated for a discrete component $n = 5$ section transmission line considering $R_L = 1000\,\Omega$ and $\tau = 100$ ns using (1) and (2). The output of the gate pulse was connected to the accelerating grid through a capacitor to isolate the high voltage present on the grid with gate circuit.

3.3 *Trigger pulse circuit*

A fast ($\leqslant 1{\cdot}5$ ns rise time) trigger pulse generator was developed to trigger the sweep as well as the intensifier circuit. The block diagram of the circuit is shown in figure 7. This pulse generator employs transistors (2N5551) in avalanche mode as switching elements. A capacitor of 40 pF was charged up to 300 volts and discharged through a resistive divider to provide pulses of ~ 50 volts amplitude and $\leqslant 3$ ns duration across a $50\,\Omega$ load. It could be operated in manual, external or internal modes. The frequency of operation in the internal mode was from 10 Hz to 100 kHz. Manual operation in this generator was achieved by using 4001 CMOS ICs in mono stable mode where IC_1 acts as a buffer and IC_2 acts as dual monoshot IC. Internal mode operation of the generator was achieved using 4047 CMOS IC in a stable mode as shown in figure 7, where the frequency of operation from 10 Hz to 100 kHz was achieved by proper selection of R and C. The transistor T2 (2N5551) had a $50\,\Omega$ resistance at its base for triggering



FREQUENCY	C
10Hz	0.1uF
100Hz	0.01uF
1KHz	1KpF
10KHz	100pF

Figure 7. Trigger pulse generator circuit.

purposes. Since CMOS ICs can drive only high impedance loads, another transistor T1 (2N5551) was used in the saturation mode to amplify the current level. The external triggering of the generator was achieved by direct application of an external trigger at the base of the transistor T2. The mode of operation, that is internal, manual or external is obtained with the help of a DPDT switch. The fast electrical pulse obtained from this circuit is shown in figure 8.

3.4 *Biasing power supply*

Several DC high voltage power supplies are needed to drive the picosecond streak camera. The photocathode, accelerating grid and focussing electrode of the X-ray streak camera require biasing voltages of -12, -10 and -11 kV respectively, with

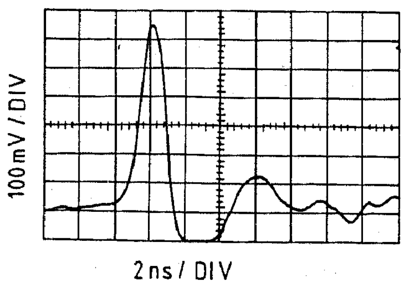


Figure 8. Oscillogram of the fast trigger pulse recorded on Lecroy model 9360 oscilloscope (5 GHz).

respect to the anode and the phosphor screen. A 4·5 kV power supply drives the sweep voltage and the gate circuit whereas a variable ± 500 V supply controls the position of the streak on the screen. Similar power supplies were used to test the optical streak camera also instead of the − 15, − 15, − 13 kV biasing voltages required for photocathode, accelerating mesh and focussing electrode respectively.

4. Setup for streak camera testing

4.1 *Laser diode: A source for optical streak camera*

A single heterojunction GaAs laser diode LD-62 emitting at 904 nm was used as an optical source for testing the optical streak camera. These optical pulses were generated with the help of a driving circuit (Rai *et al* 1995a) having series stack of two 2N5551 transistors operating in avalanche mode (figure 9). A capacitor of 40 pF charged to ~ 600 volts was discharged through the laser diode. The peak current in the laser diode was decided by charge stored in the capacitor ($Q = CV$). The value of C and V can be changed according to the requirement of current in the diode. The rise time and pulse duration of the electrical pulse were recorded as ~ 1 ns and ~ 2·5 ns respectively. The current pulse duration depends on the value of C and the resistance in the discharging path. However, an attempt to reduce the rise time and the time duration of the current pulse by increasing the breakdown current was not successful. The laser diode driver circuit was triggered by the trigger pulse generator described in § 3·3. Trigger pulse was applied through a fast transmission line pulse transformer to isolate the driver circuit with other components. The laser diode (LD-62) obtained from Laser Diode Incorporated, USA has a lasing threshold current ~ 6 A, maximum peak forward current ~ 20 A and total peak radiant flux 5–6 W with peak emission wavelength at 904 nm. There is no critical requirement of power (radiant flux) emitted from the laser diode to test the streak camera. Even a diode laser operating below the threshold current of lasing (spontaneous emission mode) can be used to test the camera due to its better sensitivity. This diode was mounted on an aluminium block which acted as a heat sink. The circuit diagram of the laser driver is shown in figure 9. The laser diode was operated in three modes, (i) manual mode (ii) external trigger mode and (iii) internal trigger mode. Optical pulses were available with repetition rates varying from 10 Hz to 10 kHz when operated in internal mode and in single pulse when operated in external or manual mode. The laser diode could provide the smallest light pulse of 120 ps time duration.

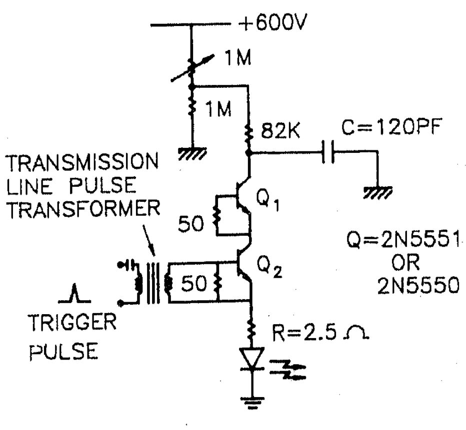


Figure 9. Driving circuit for the laser diode.

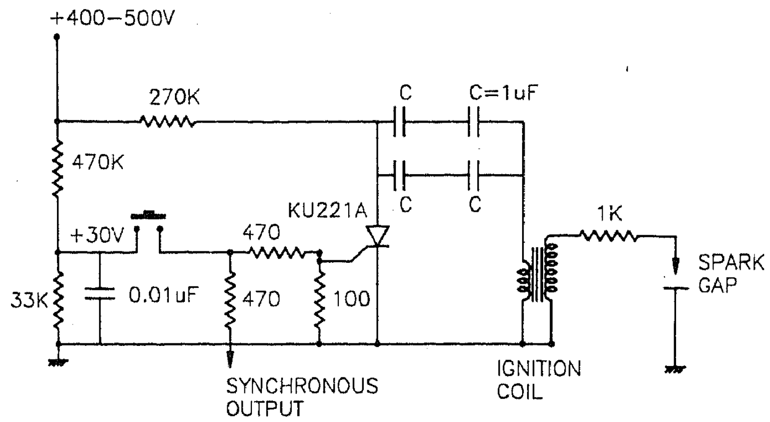


Figure 10. Circuit diagram of the spark gap driver.

4.2 *Source for testing X-ray streak camera*

Two types of sources were used to test the X-ray streak camera, (i) UV radiations from a spark gap kept in a vacuum chamber and (ii) soft X-rays emitted from the laser produced plasmas.

4.2a *Spark gap driver*: Figure 10 shows the circuit diagram of the spark gap driver. In this circuit 1 μF capacitor charged up to ~ 400 V was discharged through the ignition coil by triggering the SCR. It provided a high voltage pulse at the output of the ignition coil which was connected to one of the electrodes (pin-like sharp) of the spark-gap (kept in 10^{-5} torr vacuum and separated by a fraction of a millimetre), whereas the other electrode was grounded (a plate). About 5 kV pulse applied on the spark gap produced a spark of duration $\sim$ 1–3 μs. It has been reported (Dashevsky *et al* 1988) that the radiation spectrum of such a source has a maximum in the UV range and has sufficient power to produce a bright image of the slit on the screen of the streak camera. This source was operated manually. This driver was used to test the operation of streak camera for nanosecond time resolution. Low energy reproducibility in different shots is the main disadvantage of the spark gap driver. Pulsed UV emissions from the spark gap were studied using a slow sweep voltage ($\sim$ 5–20 μs) applied on the deflection plates of streak camera which are generated with the help of transistors. Experimental results indicate the presence of a substructure of $\sim$ 100 ns duration within the flash duration ($\sim \mu$s).

4.2b *X-rays from laser produced plasma*: The short time duration X-rays generated from the laser produced plasma are used as a source to test the picosecond X-ray streak camera. The experimental system (figure 11) consists of a target chamber of 20 cm diameter and 20 cm height with 6 ports in radial directions out of which 4 ports are at 90° and two ports are at 45° in comparison to the port which is used for passing the laser beam. The streak camera was attached to the chamber at a port 90° to the laser axis. A copper target was kept at the centre of the chamber evacuated upto 10^{-5} torr. A 35-picosecond mode locked Nd:YAG laser delivering 75 mJ energy was focussed onto the copper target to produce the plasma and as a result a subnanosecond duration soft X-ray pulse was emitted. A portion of the laser pulse energy was used as a reference

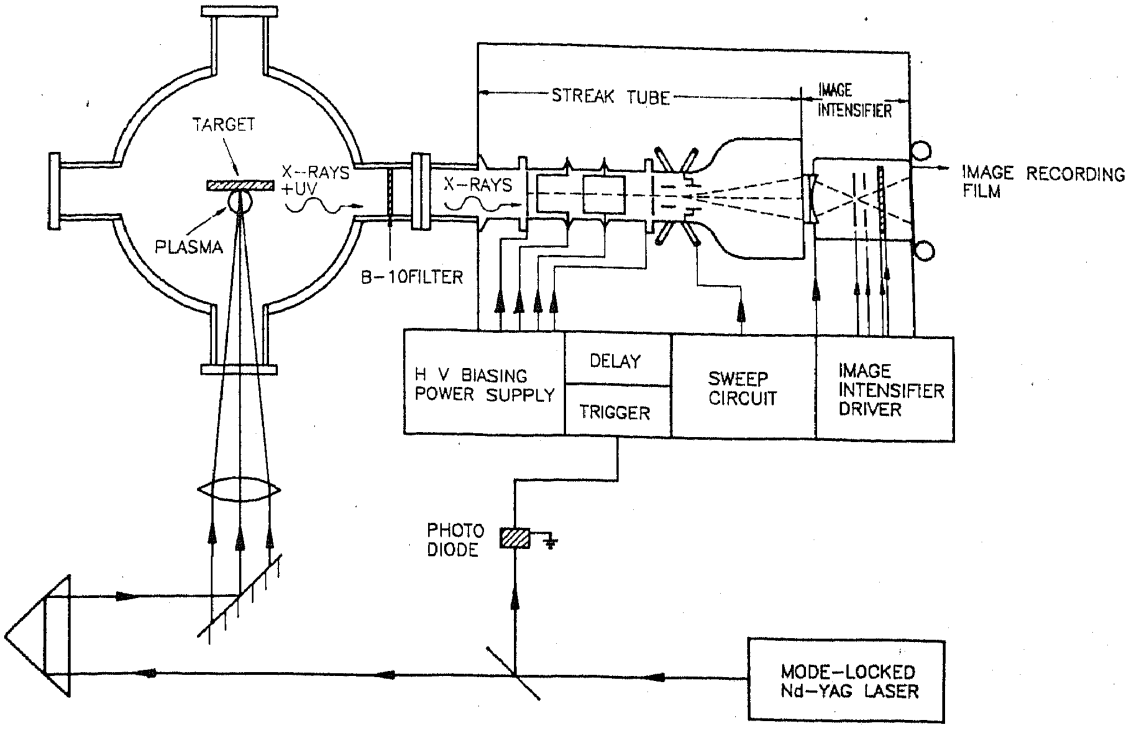


Figure 11. Experimental set-up for testing X-ray streak camera.

for triggering the sweep and gate circuits. The main laser beam generating the plasma and X-rays was delayed by ~ 25 ns to synchronise the arrival of photoelectrons and the start of the sweep voltage on the deflection plates. Two parallel plates, one at -12 kV and other at ground voltage were kept in front of the photocathode in such a way as to deflect and collect the ions and electrons generated in the chamber avoiding any direct impact of charged particles on the photocathode. A B-10 polycarbonate foil was used to cover only half of the vertically located slit such that the open part of the photocathode was sensitive to UV and soft X-rays whereas the covered part was sensitive to soft X-rays only. A 5-ns rise time sweep streaked the image in the horizontal direction.

4.3 *Recording system*

The streaked image from the screen of streak camera was recorded on a polaroid film by the contact photography method as well as by using the CCD camera. The images recorded using the CCD camera were analysed on a personal computer using the software PROMISE (Profile Measurement of Image Size and Edge location) to obtain the temporal intensity profile of the image (Vora *et al* 1994).

5. Results and discussion

5.1 *Study of multiple pulsation in diode laser using optical streak camera*

The experimental setup for testing the optical streak camera is shown in figure 12. The optical pulse from a laser diode was focussed on the photocathode of optical streak

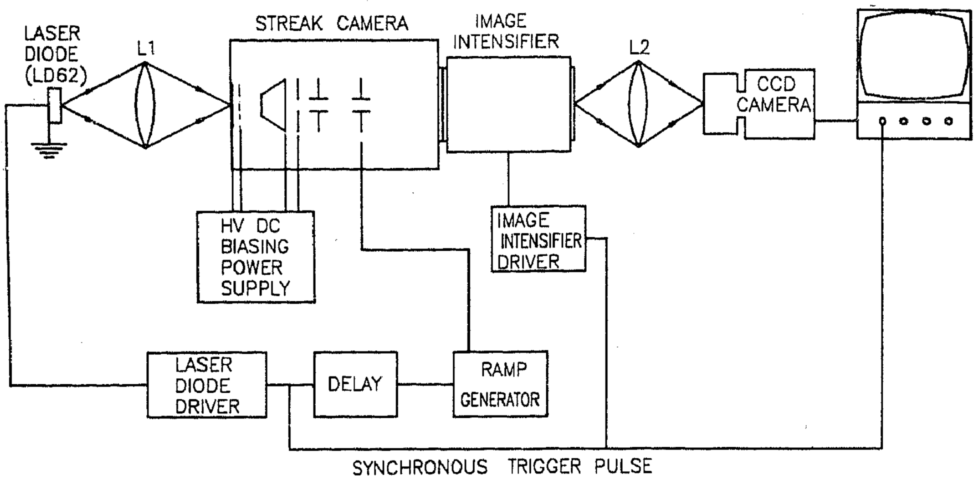


Figure 12. Experimental set-up for testing optical streak camera.

camera using an $f/1$ lens of $f = 5$ cm. The photoelectrons were streaked on the screen using a 1-ns sweep circuit and the image was recorded on the polaroid film. A second shot was taken by delaying the arrival of the light pulse by 1 ns. The images of the first and the second light pulse were separated by $\sim$ 15 mm in space which corresponds to 1 ns. This provided us with a fastest experimental streak rate of $\sim$ 15 mm/1 ns (streak velocity $1{\cdot}5 \times 10^9$ cm/s) which is less than the expected value of $\sim$ 40 mm/1 ns. This is due to the capacitive loading of the deflection plates which slows down the sweep rise time to $\sim 2{\cdot}5$ ns and ultimately provides less streak velocity. By shifting the single optical pulse on screen using a known delay in steps we found the linearity in the sweep within 10%. The measurements indicate that the smallest duration light pulse from the laser diode lasts for $\sim$ 120 ps when the charging capacitor is $\leqslant$ 40 pF. The pulse duration increases to $\sim$ 180 ps for a capacitor value of 120 pF (figure 13). This indicates that the optical pulse duration is dependent on the RC time constant of the circuit and intensity is dependent on the product of capacitance and the charging voltage. Figure 14 shows the variation of light intensity emitted from diode laser with the pumping current which was recorded using the photodiode. Here the diode laser was operated by discharging two capacitors C = 270 pF and 120 pF one by one. This indicates that the emitted intensity increases slowly up to the threshold ($I_0/I_{\mathrm{Th}} \sim 1$) and then increases very quickly. The intensity variation was similar whether the diode laser was operated

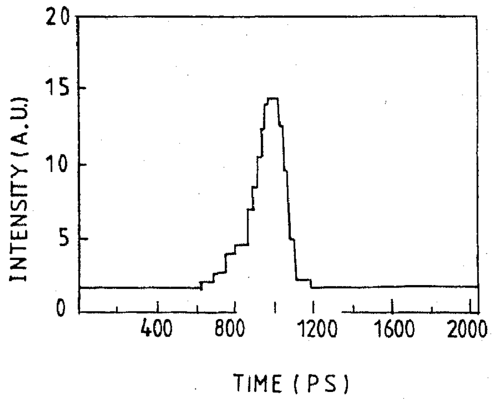


Figure 13. Single optical pulse emitted from laser diode and recorded using optical streak camera.

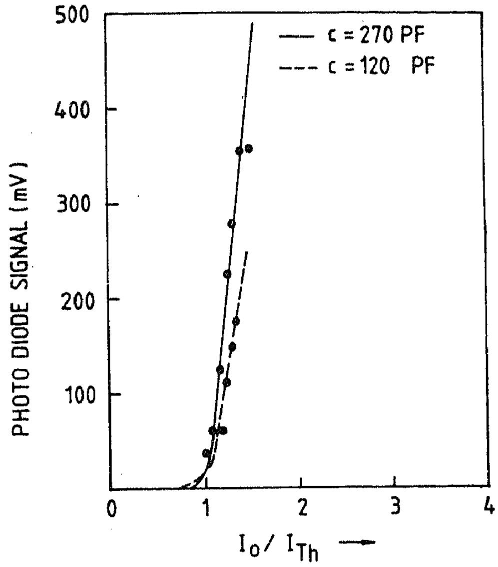


Figure 14. Variation of optical intensity emitted from laser diode with pumping current pulse (injection current/threshold lasing current).

by discharging $C = 270\,\mathrm{pF}$ or by $C = 120\,\mathrm{pF}$ except for a higher lasing threshold in the latter case. It was noticed that a single optical pulse was obtained just above the threshold current for lasing. By increasing the current above the threshold, i.e. the charging voltage on the capacitor, the number as well as the duration of the light pulse emitted from the diode laser increases (Rai *et al* 1995b) (figure 15A). A further increase in the laser diode current decreases the time separation between the emitted light pulses which ultimately merge with one another to form a long duration pulse similar to a current pulse. This type of behaviour has been observed earlier in various cw and pulsed semiconductor diode lasers (figure 15B, from Elliot *et al* 1983), and is known as self-sustained pulsation (Chik *et al* 1980; Elliot *et al* 1983; Lau *et al* 1983; Yariv 1985; MacFarlane & Tatum 1992; Rai *et al* 1995a). These pulses occur at certain frequencies which coincide with the relaxation oscillation frequencies of the diode lasers (Rai *et al* 1995b). Figure 16 shows the variation of experimentally observed relaxation oscillation

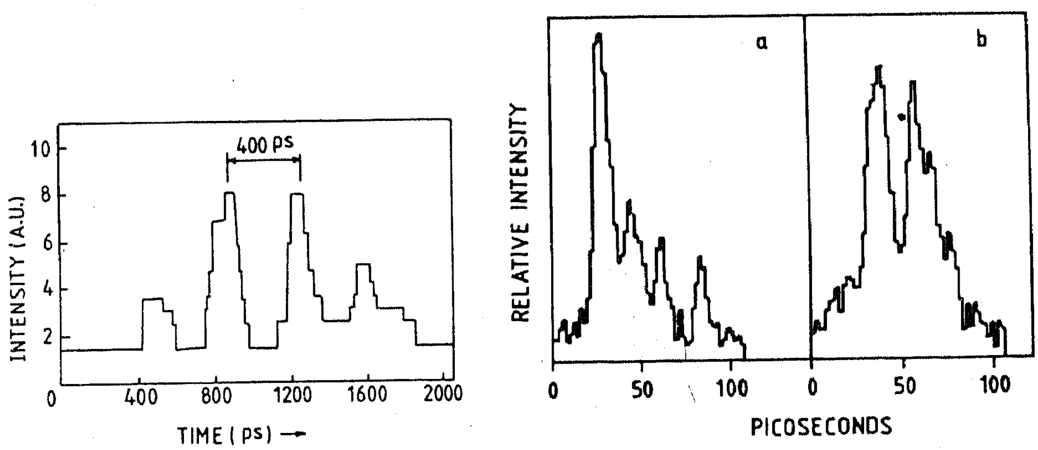


Figure 15. (**A**) Multiple pulsation observed in laser diode emission at $I_0/I_{\mathrm{Th}} \sim 1{\cdot}32$ which is recorded using optical streak camera. (**B**) Multiple pulsation observed with GaAlAs diode laser. (a) and (b) are two typical examples of individual pulses (Elliot *et al* 1983).

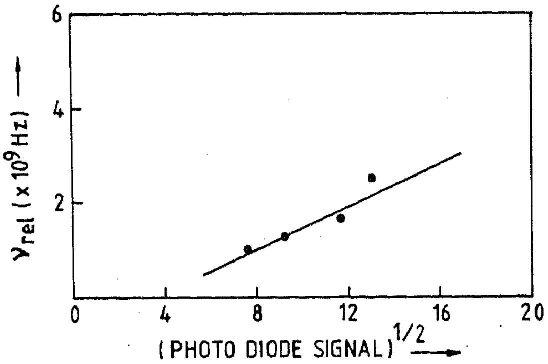


Figure 16. Variation of measured relaxation oscillation frequency with the root of intensity emitted from diode laser.

frequencies (ν_{rel}) with the square roots of the emitted light intensities, proportional to the photodiode signals. A linear variation of data points indicates better agreement with the relation given by Lau *et al* (1983) for relaxation oscillation frequency as

$$\nu_{rel} = (1/2\pi)(AP_0/\tau_P)^{1/2}$$

where P_0 is the steady state photon density in the active region, τ_P is photon life time and A is optical gain coefficient. This could be because (Yariv 1985) optical pulse generation combining the relaxation oscillation phenomenon of laser diode with the large current capability of avalanche transistors can lead to optical pulses of $\sim$ 100 ps width. According to Baker (1991) if the current impulses of the avalanche transistors return to zero before the occurrence of the second oscillation of the laser diode, only one optical impulse will be generated, whereas a current step applied on laser diode generates a train of pulses. This type of phenomena (Chik *et al* 1980; Elliot *et al* 1983; MacFarlane & Tatum 1992) seems to be due to the presence of defects in the laser cavity. These defects act as saturable absorbers for laser light and, as a result, produce small time duration optical pulses. Detailed emission characteristics of these diode lasers are published elsewhere (Rai *et al* 1995b).

This phenomenon of multiple pulsation observed in the laser diode, has been used to test the streak camera (Rai *et al* 1995a). Figure 15 shows the intensity profile in time of a laser diode emission at $I_0/I_{Th} \sim 1{\cdot}32$ where I_0 and I_{Th} are the pump and threshold currents of the diode laser. It shows the time period of repetition of pulses as $\sim$ 400 ps. Figure 17 shows a similar period of repetition ($\sim$ 400 ps) when optical pulses were

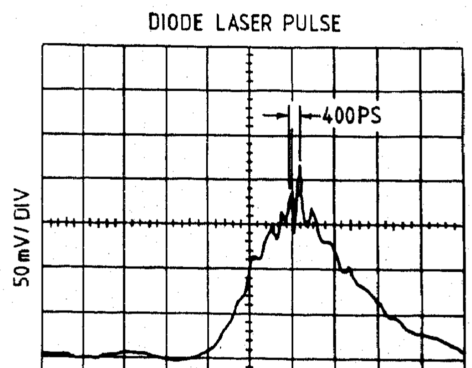


Figure 17. Multiple pulsation similar to figure 14 but recorded using L&T Gould model 7074 oscilloscope (100 MHz).

recorded using a fast photodiode and an oscilloscope (L and T gould model 7074) in equivalent time sampling mode. This indicates the successful operation of the streak camera. The equi-distant optical pulses provided similar information about the linearity of the sweep (within 10%) as well as similar streak velocity ($\sim 1{\cdot}5 \times 10^9$ cm/s) as was observed by shifting the single optical pulse as discussed before. Comparison of figures 15 and 17 indicates that the streak camera record has two equal intensity peaks between two small pulses, while the CRO trace has a single central pulse of large intensity. The above discrepancy is due to the amplitude jitter in the diode laser emission because figures 15 and 17 were recorded during two different shots. In each and every shot the amplitudes of the optical pulses changed, while the nature and time period between the pulses remain the same. However, a time jitter of ~ 500 ps has been recorded from one shot to another.

5.2 *Temporal resolution of optical streak camera*

The temporal resolution of streak camera is mainly dependent on three factors (Tsuchiya 1983); (i) the transit time spread which is caused by the initial velocity distribution of the photoelectrons emitted from the photocathode at the same time. This occurs in the low velocity domain between the photocathode and the mesh electrode and is given by

$$t_1 = 2{\cdot}34 \times 10^{-6}[(\Delta\varepsilon)^{1/2}/E], \tag{3}$$

where $\Delta\varepsilon$ is FWHM in energy distribution of the emitted photoelectrons which is $\sim 0{\cdot}4$ eV when a photon of 904 nm falls on the S1 photocathode. E is the accelerating electric field near the photocathode which is $\sim 10^6$ V/m in our case, and can provide a time spread $\Delta t_1 \sim 1{\cdot}5$ ps. However, a small time spread will exist between the mesh and the phosphor screen, which is very small in comparison to this time.

(ii) The technical or streak limited time resolution is given by

$$\Delta t_2 = 1/\delta v, \tag{4}$$

where $v \sim 1{\cdot}5 \times 10^{10}$ mm/s is the measured streak velocity and $\delta \sim 10$ lp/mm is the measured spatial resolution of the streak camera. This provides $\Delta t_2 \sim 6{\cdot}6$ ps.
(iii) The time spread Δt_3 which occurs due to the effect of the deflection electric field on the photoelectron beam. It depends on the beam diameter, length of the deflecting plate, the deflection electric field and on the axial (directional) velocity of the electrons. This time spread is typically ~ 1 ps. The actual time resolution of streak camera Δt will be given by

$$\Delta t = (\Delta t_1^2 + \Delta t_2^2 + \Delta t_3^2)^{1/2} \tag{5}$$

which comes out to be ~ 7 ps. This is the estimated time resolution of the streak camera obtained using (5).

The time resolution of this streak camera was measured using a Michelson interferometric system with a mode-locked Nd:YAG laser (M/s Continuum, USA). The main beam was split into two beams and was directed towards a pin hole which was focussed on the photocathode of the streak camera. By moving one of the two mirrors of the interferometer one pulse was delayed with respect to the other according to the requirement. This experiment provided the time duration of the laser and time

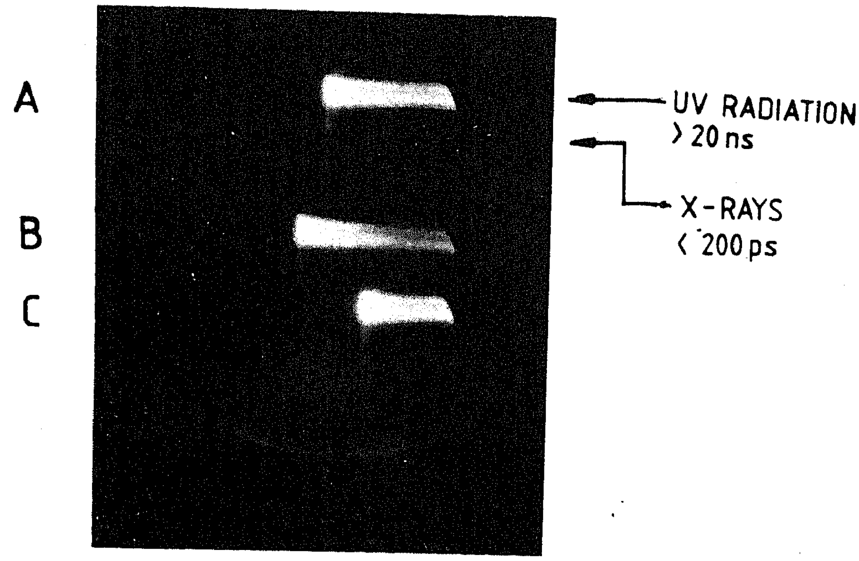


Figure 18. Contact photograph of streak image of X-rays and UV emission from laser produced plasma. A, B and C are images of different shots.

resolution of streak camera as a ~ 39 ps and ~ 40 ps respectively. However, time resolution was also calculated using the following relation

$$\tau_M = (\tau_R^2 + \Delta t^2)^{1/2}, \tag{6}$$

where $\tau_M \approx 39$ ps and $\tau_R \approx 35$ ps are the measured and reported (M/s Continuum, USA) time durations of the Nd:YAG laser pulse respectively. Equation (6) provides a time resolution $\Delta t \approx 17$ ps which is more than the expected value of ~ 7 ps and less than the measured value of ~ 40 ps. This indicates that the measured value of time resolution is being limited by the large time duration of the test pulse (35 ps). Even 10–20% error is possible in the measurement of time duration from the recorded images. These factors can lead to increased value of measured time resolution. This indicates the necessity of a smaller time duration optical pulse as well as a good optical image recording system for the measurement of time resolution of the streak camera. However, optimization of the camera parameters, such as biasing voltages, wiring arrangement in streak camera at deflection plates and improvement in optical imaging system at the input and output of the camera will essentially provide an even better time resolution and accurate time information about the events.

5.3 *Study using X-ray streak camera*

Figure 18 shows the photograph of UV and X-ray radiations emitted from the laser produced plasma using a 35 picosecond mode locked laser irradiated copper target. The time duration of UV radiation was found more than 20 ns whereas, X-ray emission last for < 200 ps. The streak rates were found as ~ 8 mm/ns and 15 mm/ns when a sweep voltage of 5 ns and 1 ns rise time were used respectively. These parameters are similar to that of an optical streak camera because of the similarity in the streak and intensifier tubes along with its driving electronics systems.

Inspite of all similarity in both the cameras, the photocathodes used are different. The transit time spread (Δt_1) of photoelectrons emitted from gold photocathode (energy spread, $\varepsilon = 5$ eV) in the case of X-ray streak camera, is calculated to be ~ 5 ps. This factor leads to a higher value of time resolution than the optical streak camera. The expected time resolution for this streak camera is ~ 15 ps. However, we could not find the experimental value of time resolution for X-ray streak camera due to experimental limitations.

6. Conclusions

In summary, we have developed an optical and an X-ray streak camera which is operating successfully with a fastest streak speed of $\sim 1{\cdot}5 \times 10^9$ cm/s and temporal resolution of ~ 17 ps (optical streak camera). Since the sweep circuit developed for this purpose provides a positive and negative polarity ~ 1 kV amplitude pulse with a rise time < 1 ns, therefore, an improvement in wiring arrangement for applying sweep voltage to deflection plates and an optimization of the biasing voltages along with better input and output imaging and recording systems will improve the streak speed and time resolution of the streak camera. However, to measure the time resolution accurately it is necessary to have an optical pulse of few ps time duration. A combination of trigger pulse generator and laser diode driver circuit used with single heterojunction GaAs laser diode provided a simple and stable picosecond optical pulse generator which generated a single as well as multiple pulses depending on the amplitude of input current flowing in it. It was used successfully to test the optical streak camera.

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