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TEN-PICOSECOND STREAK CAMERA FOR THE LASER FUSION PROGRAM AT LLL

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ABSTRACT

The development and operation of 10-picosecond streak cameras in the LLL laser fusion program are described. In addition, modifications to two TRW Model 1-D high-speed streak cameras are discussed. The compact cameras are completely self-contained, weigh about 27 kg, and occupy about 1/6 m^2 of bench space. Power consumption is less than 10 W.

INTRODUCTION

With the realization of mode-locked lasers came the ability to generate picosecond duration pulses. Resolution capability of diagnostic tools had to be improved in order to diagnose these pulses accurately. Since photon detectors (diodes and multipliers) and oscilloscopes are limited to a temporal resolution of about 200 psec, it became clear that a new approach was needed.

*Work performed under the auspices of the U.S. Atomic Energy Commission.

One successful technique involves the two-photon fluorescence (T. P. F.) characteristics of some dyes.[1] This process is very useful for measuring time separation of closely spaced pulses but, by its nonlinear nature, is not useful for accurate pulse width measurements; in addition, since the pulse autocorrelates, all pulse shape information is lost.[2] Further, the tens of millijoules of laser input required limits its applications.

Another approach uses a swept or streaked image of a slit apertured beam. Mechanical streak camera resolution is limited[3] to about 10 nsec so the sweep must be done electronically. The light to be analyzed is passed through a narrow (25 μm) slit, the image of which is focused onto a photocathode of an image converter tube (see Fig. 1). Using parallel deflection plates, the electrons emitted from the cathode are swept across a phosphor screen. The phosphor output is then intensified and recorded on film. Typical high-speed image converters* in use today are a modified English Electric Valve P856[4]; Type STM, made by Instrument Technology, Ltd.; Russian types UMI-92 and the "picochron"[5,6]; and the RCA C734435.[7,8]

We use the RCA tube. Analysis and theory of the streaking tube electron optics and transit-time considerations have been well treated and will not be repeated here.[3, 9-12]

The fast rise, linear sweep voltage necessary for the image converter tube has been generated in the past by using spark gaps, thyratrons, and Krytons.[10, 11, 13-15] Since mid-1971, we have been successfully using strings of light-triggered avalanche transistors.[16,17]

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*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

THE BREADBOARD

Our introduction into the ultra-fast streak camera field began when we modified a TRW Model 1D streak camera by adding avalanche transistor sweep and gating circuitry and a magnetically focused intensifier. Figure 2 shows the breadboard except for a rack of power supplies. The RCA C-73435AG image converter tube with an S-1 photocathode and a set of one-axis deflection plates was used here as in later models, although the fiber optics output face plate is not necessary here since lens coupling is used. This tube has a shutter grid which is biased to +2650 V instead of the normal 200 V. The shutter grid is thus used as an extraction grid[9] providing a 3000 V/cm field at the cathode. The effect is to reduce the total transit time of electrons from the cathode to the screen, thereby reducing transit time spread due to initial velocity spread of about 0.3 eV of the electrons emitted from the cathode. This results in improved system temporal resolution. The breadboard has been in almost continuous use since it was built in the fall of 1971.

THE COMPACT CAMERA

The breadboard system requires 2 men and a small fork lift to relocate. It also requires about 3 m^2 of floor space and 208 V power input (a total of 1.5 kW). A more compact system was in order. The results of our efforts to develop one are shown in Fig. 3.

All power supplies were miniaturized and mounted within the camera body. Avalanche transistor gating and sweep circuitry was also used. The greatest contributing factor to compactness was the use of a proximity coupled, proximity focused, microchannel image intensifier. The compact system weighs 27 k gm (60 pounds), is completely self-contained, requires 1.6 m^2 of bench space and only 8.5 W of power at 120 V. (The electric shutter requires an additional 14 W.)

As shown in Fig. 3 a filter holder and adjustable slit are adapted to a Tektronix C-27 camera assembly, which is used for its convenient structural rigidity as well as the f 1.4 lens and shutter. The C-27 focal plane is flat, so a negative field correcting lens was used in front of the cathode to curve the focal plane to conform to the cathode curvature.

The main body of the camera houses the streak tube, power supplies, avalanche sweep and gate electronics, and controls for adjustments and mode selection. Figure 4 shows one of the compact cameras with the side access door open to display the sweep generator board. Coupled to the streak tube by fiber optics (index matching fluid is also used) is the intensifier tube. Film is directly contacted to the intensifier fiber optic output by the camera mechanism, which provides for use of either a Polaroid holder (for Type 107 film which has an ASA 3000 rating) for setup and much of our work, or a hard film holder (for film such as Royal X-Pan which we develop to ASA 2000) when densitometer readings are desired.

IMAGE INTENSIFICATION

Conventional commercial streak cameras without intensifiers (such as the TRW 1D, Thompson-CSF Model TSN 320 and the Hadland Imacon) have temporal resolutions in the 50 to 100 psec region. If a conventional camera with coupling lens is used, a coupling efficiency from the streak tube output to film of from 1 to 5% can be expected. Substituting proximity coupling to the film would increase light coupling efficiency by a factor of approximately 20. With this increase one might expect to be able to increase the writing rate by a factor of 20 and achieve 10 psec resolution directly without further intensification. However, factors such as deflection plate transit time dispersion assume more significance at higher sweep rates and are affected by dispersion due to Coulomb repulsion in the electron beam as it travels through the tube. Coulomb repulsion dispersion is a function of the beam current density and, hence, can be reduced by reducing the beam current density. When this is done, itensification becomes necessary in order to expose film properly. The three-stage magnetic 89 mm intensifier used in the breadboard system has a gain of 5×10^4, which produces an effective exposure enhancement on film (EEIF) under pulsed conditions of only about 100 times (due to coupling loss in the lenses). The three-stage magnetic, 40 mm intensifier used in one of the TRW 1D modifications (discussed later) has a gain of 10^5 and achieves a pulsed EEIF of 800 by using a reducing magnification of 0.5:1 (which increases the intensity 4 times, thereby being consistent with the above). The fiber-optic coupled 40 mm proximity focused channel plate tubes have measured P11 radiant power gains of 2 to 6 × 10^4 and a typical pulsed EEIF of about 5000 times when used in the compact camera. The second TRW 1D modification uses a 40 mm microchannel plate tube, lens coupled to the streak tube but proximity coupled to film. The rated brightness gain is 5000, which yields an EEIF of 1000.

It has become clear that, aside from the very significant reduction in weight, size and power consumption, the channel plate tube offers a higher effective gain when proximity coupled. Also, when power supplies are included, these channel plate tubes are economically competitive with the magnetic tubes.

Due to proximity coupling to the film, no mechanical shutter can be interposed. The noise seen on the output of the channel plate tubes is primarily produced by the cathode and is essentially eliminated by gating off the cathode. Shuttering is therefore accomplished, preventing film from integrating noise, by gating on the cathode voltage for about 100 μsec during the exposure time. A 100-μsec one-shot triggered by a "wand" pickup near the sweep avalanche transistors, by a low voltage tap in the gate board, or by an external input, drives the power supply gate input. Also, on the same p. c. board there is a 1-sec one-shot which is triggered by the first one-shot and drives a Mallory model SC 628 Sonalert beeper, giving an audible indication that the camera has been triggered. This has proven extremely useful for monitoring whether the laser has fired, the camera has operated, or, if the beep is continuous in the absence of the laser pulse, there is a problem in the avalanche transistor circuit.

SWEEP AND GATE CIRCUITRY

AVALANCHE TRANSISTOR SELECTION. Our avalanche transistors are selected from the 2N3700 standard line. The 2N3700 chip is the same as the chip for a 2N3019, but it comes in the smaller TO-18 can.

SELECTION TECHNIQUE. With a 200-ohm base-emitter resistor, those transistors were selected which avalanche between 1 and 5 mA with an avalanche (or Zener) voltage between 185 and 205 V. Monitoring of the noise level with a scope is used to insure they have a noise or grass level below 1/2 V in the range of 50 to 400 μA, which covers the 80 μA bias region where they are used in the sweep and gate circuitry. Transistors with a "mushy" knee in the Zener region tend to be quiet but have a long trigger delay and should not be used. Those with Zener voltages above 210 V tend to avalanche spontaneously and must be avoided. Spontaneous avalanche also occurs with some units below 1 mA. These units must not be used since if one transistor fires, it will trigger the rest of the string.

OPTICAL TRIGGER. The laser triggered transistors are prepared by removing the top of the can with a special transistor can cutting tool ("Can Opener" made by Motorola). We formerly cemented a small glass lens over the hole, but we found that this is not necessary and the transistors are now used with the chip exposed as shown in Fig. 5. The laser beam is then directed onto the exposed chip.

RELIABILITY. Avalanche transistors, by far, have the most deleterious effect on camera reliability. The greatest problem with transistor reliability has been operator familiarity. Once the operator learns how to set the trigger energy to accomplish triggering without exceeding the damage threshold, few failures occur. Cameras, once set up, typically operate for months without a transistor failure. When failure does occur, it seems to be the spontaneous avalanche of one transistor. This, in turn, causes the entire string to avalanche at a several-kHz rate, resulting in high power dissipation in the transistors and damage to other transistors in the string. The "beeper" alerts the operator to a fault and allows the system to be shut down and repaired before damage to other transistors occurs. Shorting adjacent transistor cans sequentially with a metal tipped plastic probe until the "beeper" stops easily locates the bad transistor (if only one is present). Alternately, the entire string of transistors can be replaced with a new, previously selected set in a matter of a few minutes and the bad one(s) can be located later.

Trigger threshold for the trigger transistor is 30 nJ at 1.06 μm (with a 30 psec pulse) when the transistor string bias current is 80 μA . An operating bias of 80 μA was picked because most of the transistors have a major part of their noise below 60 μA. A higher bias reduces the trigger energy but causes higher power consumption, higher operating transistor junction temperature, and a slightly greater probability of spontaneous avalanching.

The trigger level should be 10 to 100 times the threshold level in order to ensure low turn-on delay and small jitter. This puts the trigger level in the μJ region. The upper limit is set by the transistor damage threshold, which is about 1 mJ.

GATE AND SWEEP GENERATORS. Figures 6 and 7 show the sweep and gate circuits. Both can be triggered by a fast rise (5 nsec) electrical input signal of about 150 V (of either polarity) or the optical trigger transistor. Triggering of one transistor in the string is sufficient to cause avalanche of the entire string. Rise time and delay are of the order of 1 to 2 nsec.

The sweep circuit uses 20 transistors, which produce a 4000-V step across the series LRC circuit, where the C is the deflection plate capacitance plus that of C5. The resulting wave form is that of a cosine across the deflection plates. A voltage of 2800 V is needed to deflect the full 60 mm of the streak tube so an over-scan of more than 2 to 1 is achieved within our 40 mm intensifier field of view.

This allows only the middle portion of the waveform to be used (near the zero crossing) resulting in a sweep linearity of better than 10% for 40 mm (and 2.5% for 70% of the usable sweep) as determined with the aid of a 100 psec etalon placed before the camera input slit. Ringing was not detectable and with the values shown (C5 = 0), the sweep rate is between 31 and 33 psec/mm over 90% of the usable sweep. The total sweep time is 1.15 nsec for the 38 mm usable tube diameter. Increasing the value of C5 to 100 pF max (where the sweep becomes an R-C rising voltage form) will increase the sweep time to 175 psec/mm. This is sometimes a handy way to determine delay times initially.

Removel of the L (the four 0.1-μH inductors) and R (the two 51-ohm series resistors) and cutting the number of transistors to 12 will produce a sweep rate of 26 psec/mm. However, the technical resolution remains essentially the same because the spatial resolution decreases. Also, the flexibility of slowing the sweep is removed. The "wand" pickup for the beeper and intensifier gate one-shot trigger is a small p.c. wire near Q10. The time jitter between initiation and start of the sweep has been measured at less than 50 psec by noting the position jitter on several photographs of different laser pulses when laser energy from pulse to pulse is fairly constant. The setup delay time between introduction of the laser pulse to the sweep trigger transistor and its arrival at the cathode is about 2.5 nsec (70 to 100 cm path length difference). Electron transit time from cathode to the deflection plates is 2.5 nsec.

The gate circuit uses 14 transistors and produces a fast rise +2800 V step. (The tube grid is reverse biased by 150 V to cut it off so that the 2800-V gate step produces a 2650-V forward grid bias.) The Krytron (KN-6) resets the step to zero in 150 nsec (50 nsec for a KN-22). An rc delay in the Krytron gate circuit has been used to extend the gate time to several microseconds.

OPERATING MODE OPTIONS. The "Scope Trig" output can be delayed (about 20 nsec is necessary to pass the gate circuit ringing) and fed to the "Electrical trigger input" of the sweep board. This method requires only one transistor in the gate board to be optically triggered. Of course the gate and sweep may be optically triggered when an optical delay is substituted for the 20 nsec electrical delay. The gate circuit is only necessary where high ambiant (e.g., flashlamp) background is present or when a small part of a long light pulse or train of pulses is being diagnosed. For single switched out pulses, which comprise most of our sources, the gate board power supply is switched off and a +2600-V dc bias is placed on the streak tube grid. The sweep circuit is then optically triggered.

THE IMAGE CONVERTER STREAK TUBE

A film exposure threshold of the camera system for a streaked 30 psec, 1.06 μm laser pulse has been determined for several different streak tubes tested to be between 2×10^{-9} and 10^{-11} J incident on the 25 μm wide camera slit. This puts the tube sensitivity of the cathode at about 30 W/cm^2. The measured linear range of the tubes is greater than six orders of magnitude, limited on the low end about one order of magnitude below film threshold by the measuring instrument (PM tube) and tube noise and on the high end by tube saturation or the available laser energy (and the fear of burning the cathode).

The above data are for average tubes. We have encountered two tubes which were far below average, one of which may have been damaged by an external high voltage breakdown or too high a laser input energy. These tubes exhibit low cathode sensitivity (10^{-6} to 10^{-7} J at the slit) and a quadratic dependence of the output intensity on the input energy. We believe these two defects are related because at the necessary high input photon levels for low sensitivity cathodes, the probability of two-photon reactions increases. The result, besides a low sensitivity camera, is a reduction in dynamic range. One order of magnitude increase in input produces two orders of magnitude increase in output brightness, which uses up the dynamic range of the film (about 2 to 3 orders of magnitude) and of the intensifier (about 2-1/2 orders of magnitude). Screening of the tubes for sensitivity at 1.06 μm has eliminated the problem.

TRW 1D MODIFICATION

We decided to see if we could add our sweep circuit to an available TRW 1D streak camera without destroying its normal functions, as had previously been done here and by others.[9] This we did, and it worked so well a second camera was also converted.

A new bank 7B streak plug-in was purchased from TRW and the avalanche sweep circuit was installed along with two small modular dc-dc converters to produce the required plus and minus 3000 V (Fig. 8). Power was taken from an unregulated 24-V source already available in the mating plug for the 7B plugin and regulated to 12 V. A Zener diode clamp on the pin to the streak tube shutter grid must be removed (a switch can be used to reconnect it for standard operation) and 2600 V applied to the grid as before. The focus control of the camera must then be readjusted to focus for the higher grid voltage. Thus, reconnection of the Zener clamp and refocusing are all that is necessary to return the camera to its previous state.

On the first camera we used an available three-stage, magnetically focused 40 mm intensifier and on the second unit, an available 40 mm microchannel intensifier. Figure 9 shows the second unit. Both cameras equal the 10 psec resolution of the compact system. The cost to convert was less than $1000 each plus the intensifier.

These cameras, in use for the past several months now, have been applied to study time evolution of multiple orders of stimulated Raman scattering and time dependence of spatial distribution of the near field of each individual order.

PERFORMANCE

The technical resolution, determined by the streak speed and the dynamic spatial resolution of the camera, is 6.8 psec. The electron transit time dispersion is calculated to be less than 7 psec as a result of the 2000 V applied to the gating grid. Quadratic summations of these values yield an instrumental time resolution of 10 psec. Figure 10 verifies this. It is a photograph of the "single" switched-out pulse from a mode-locked Nd:glass oscillator. Each of the subpulses is about 15 psec long; they are separated by about 20 psec. Figure 11 shows what was believed to be a clean 2 nsec pulse from our Long Path Laser. The envelope contains regular, deep, 28 psec modulation and a weaker 300 psec modulation. The source of this oscillation was traced to reflecting surfaces in the oscillator cavity, producing subcavity modes. Discovery of these modes explained a problem encountered with the laser and led to its solution.

Multiple-exposure streak photographs have been used for accurately determining the width and shape of a pulse from a laser oscillator.[18] Figure 12 shows the densitometer traces of a streak record of the output of a mode locked Nd-YAG oscillator that has been pulse-stretched by the addition of some intercavity optical elements. The multiple-exposure streak record, with a known intensity ratio between exposures, is not shown. The half-width of the pulse is 140 psec and the profile is smooth. The fluctuations apparent on the curve do not reproduce from curve to curve and are caused by intensifier and film noise.

The ultrafast streak cameras have also been used to study the effects of nonlinear optical effects on high-power laser pulse propagation.[18] The time-dependent, self-focusing of pulses has been directly observed. More recently, a time resolved interferometric technique has been used to measure the refractive index changes in optical materials induced by the passage of a high power light pulse.

STREAK TUBE DEVELOPMENT

Two streak tube developments are currently underway at LLL. The first is a circular sweep tube designed for 1 psec resolution. It is currently operating under test. The second is an X-ray streak tube, the cathode of which is being developed here. This tube uses the optically triggered avalanche sweep. We will report on both of these tubes later.

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BIOGRAPHY

Author Stan Thomas has been involved for the past three years as a senior project engineer in the laser diagnostics group of the Laser Fusion program at Lawrence Livermore Laboratory. He had previously been engaged at LLL in nuclear test diagnostics in Nevada and, for 8 years, in space radiation diagnostics and measurements using sounding rockets. Stan Thomas joined LLL in 1959 after working for a year in Switzerland for Brown Boveri Corporation. His B.S.E.E. was received from the University of California.

FIGURE CAPTIONS

Fig. 1. Schematic diagram of ultrafast streak camera.

Fig. 2. Original Livermore 10-psec resulution streak camera.

Fig. 3. Schematic diagram of Livermore compact 10-psec resulution streak camera.

Fig. 4. Livermore compact streak camera.

Fig. 5. The avalanche trigger transistor with the can top removed.

Fig. 6. Avalanche transistor sweep circuit.

Fig. 7. Avalanche transistor gate circuit.

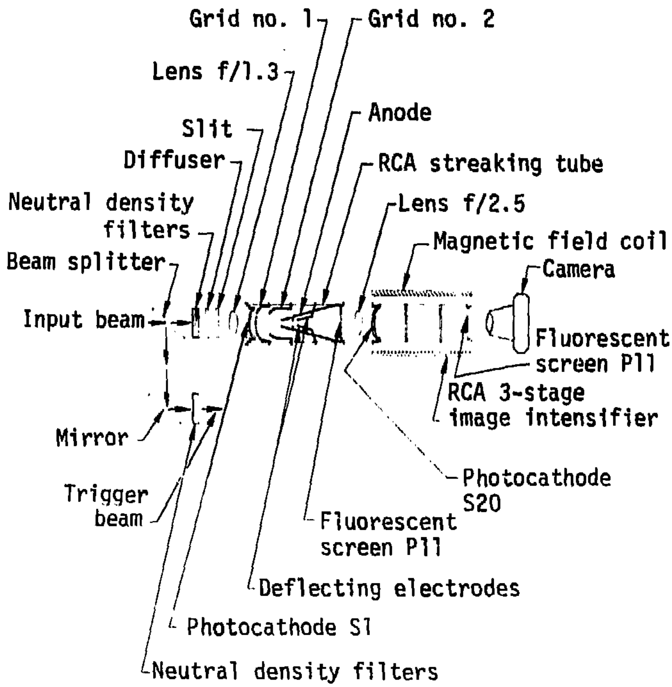
Fig. 8. The 7B plug-in frame with the avalanche sweep circuitry and power supply added.

Fig. 9. The TRW 1D camera showing the 7B plug-in on top and the camera with intensifier and power supply on the right.

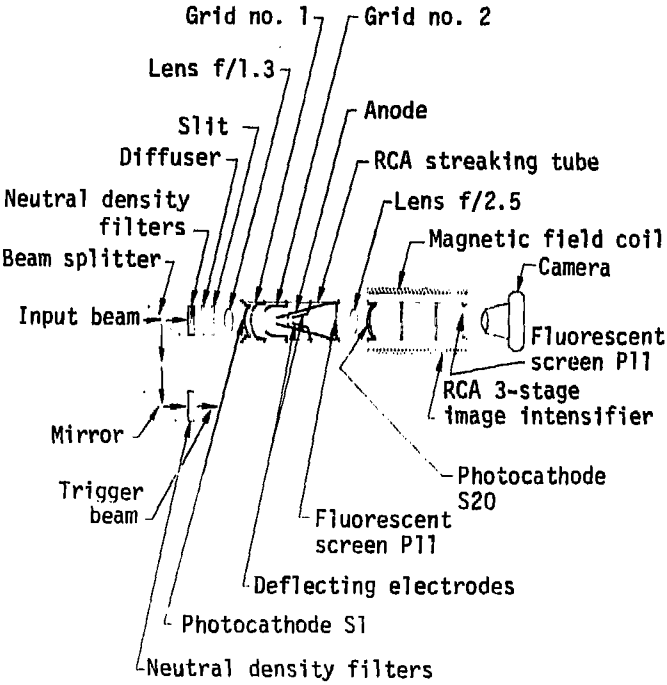
Fig. 10. Streak photograph of a mode-locked Nd:glass laser pulse.

Fig. 11. Streak photograph of laser pulse generated in the Livermore Long Path Laser.

Fig. 12. Detailed laser pulse measurement with ultrafast streak camera.


Grid no. 1
Grid no. 2
Lens f/1.3
Anode
Slit
Diffuser
RCA streaking tube
Neutral density filters
Lens f/2.5
Magnetic field coil
Beam splitter
Camera
Input beam
Fluorescent screen P11
RCA 3-stage image intensifier
Mirror
Photocathode S20
Trigger beam
Fluorescent screen P11
Deflecting electrodes
Photocathode S1
Neutral density filters

Thomas - Fig. 1


Grid no. 1
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Lens f/2.5
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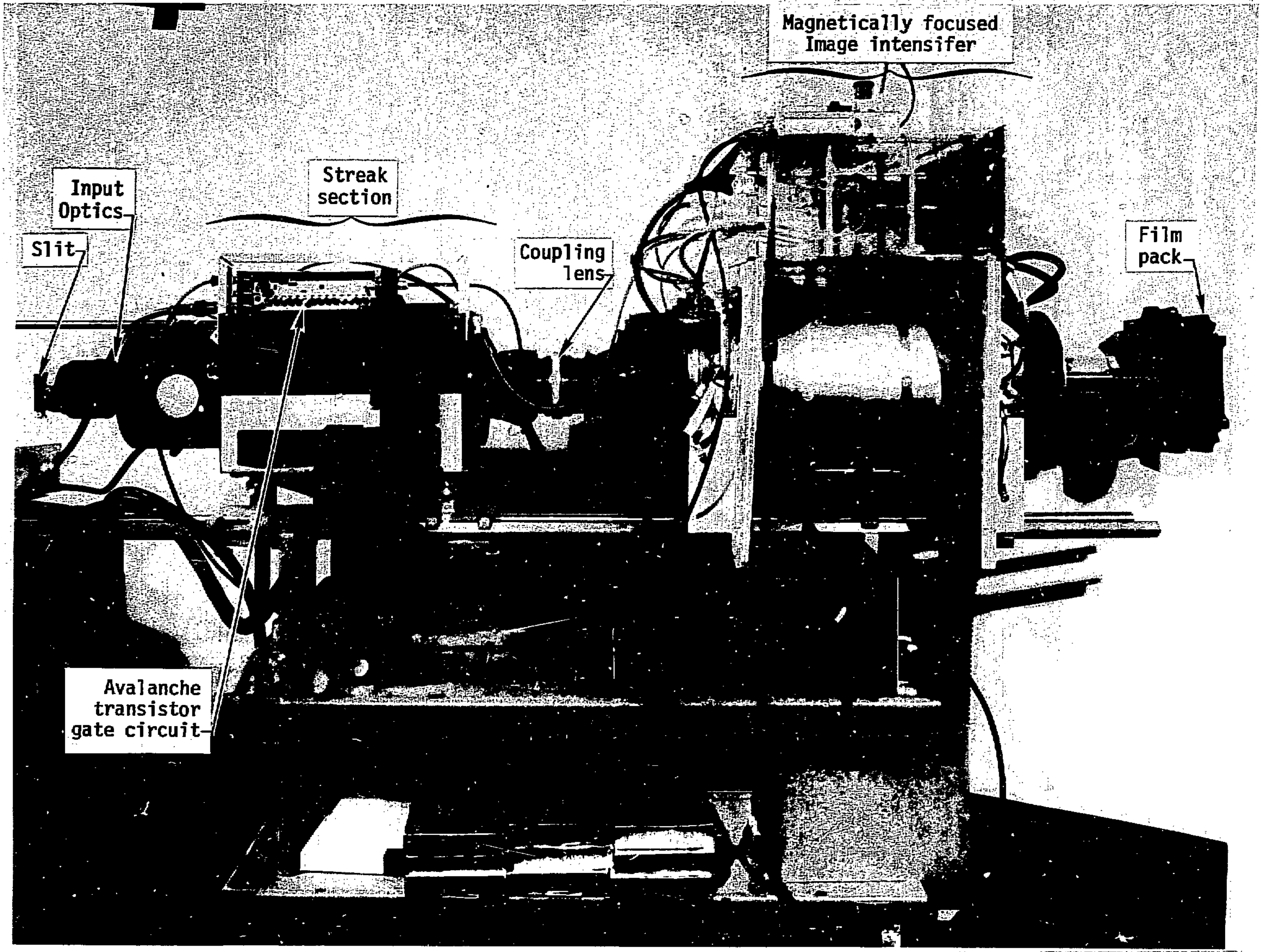
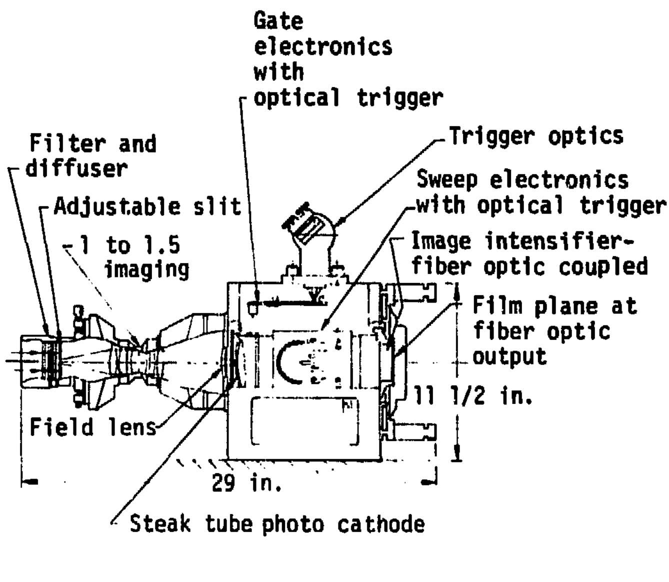
Beam splitter
Camera
Input beam
Fluorescent screen P11
RCA 3-stage image intensifier
Mirror
Photocathode S20
Trigger beam
Fluorescent screen P11
Deflecting electrodes
Photocathode S1
Neutral density filters

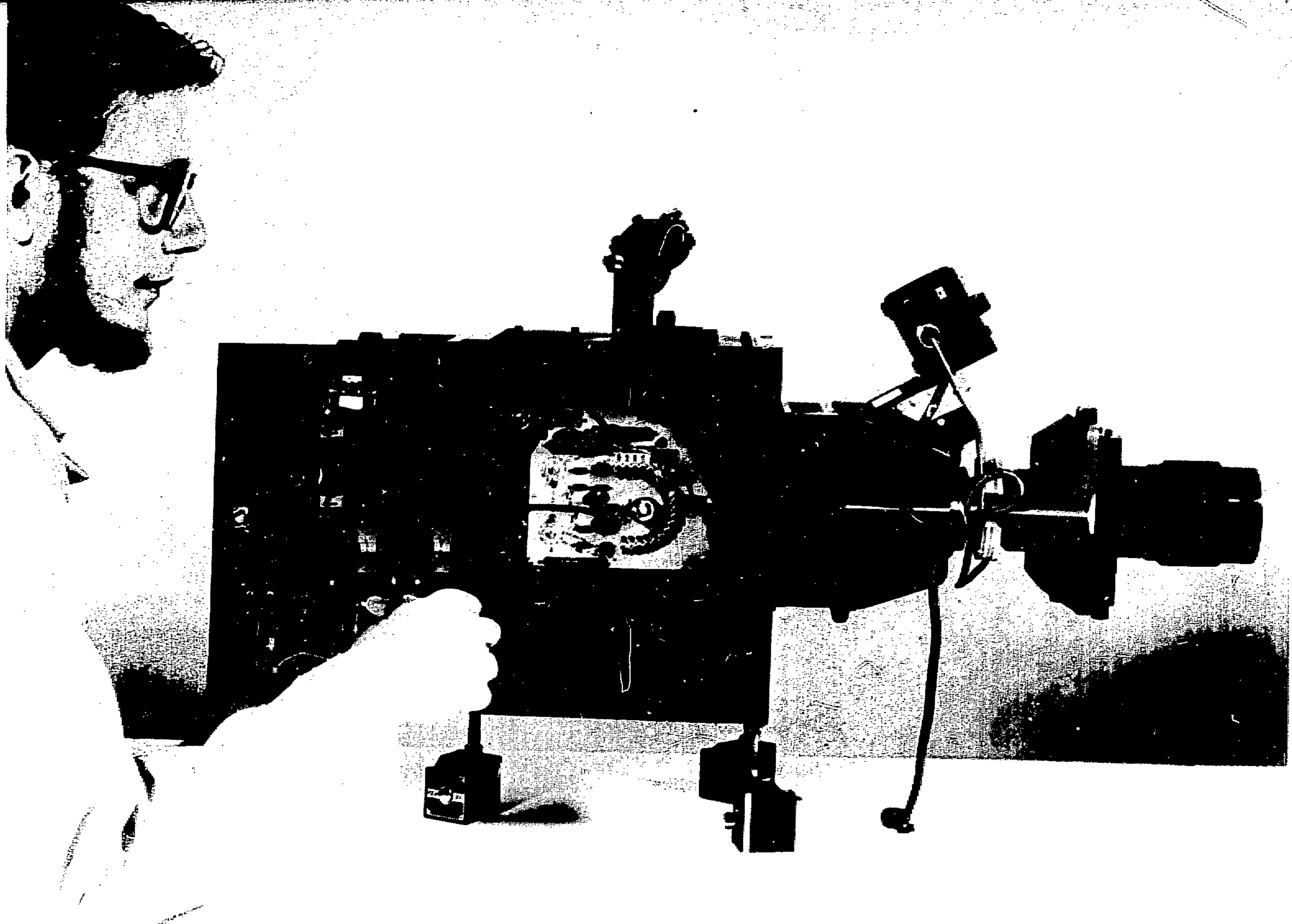
Thomas - Fig. 1


Magnetically focused
Image intensifer
Input
Optics
Streak
section
Slit
Coupling
lens
Film
pack
Avalanche
transistor
gate circuit

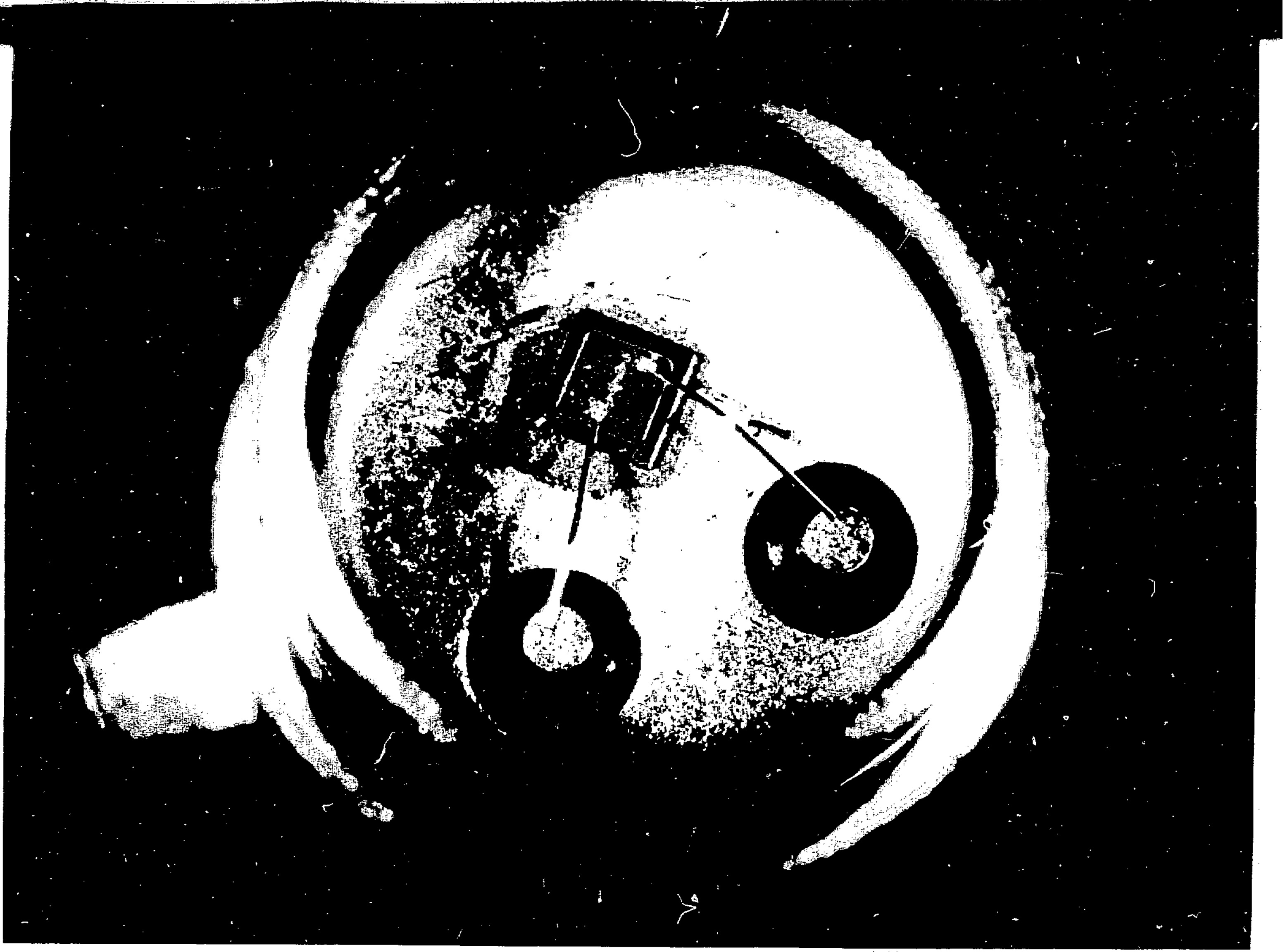
Thomas - Fig. 2


Gate electronics with optical trigger
Trigger optics
Filter and diffuser
Sweep electronics with optical trigger
Adjustable slit
1 to 1.5 imaging
Image intensifier-fiber optic coupled
Film plane at fiber optic output
11 1/2 in.
Field lens
29 in.
Steak tube photo cathode

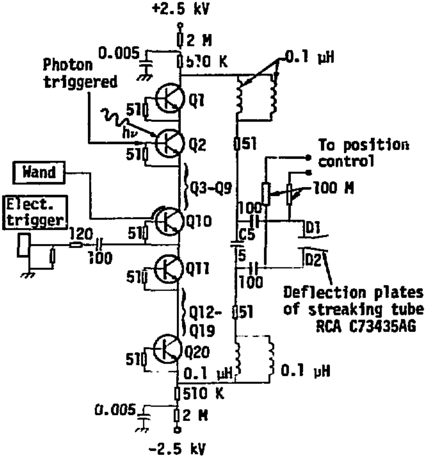
Thomas - Fig. 3



Thomas - Fig. 4



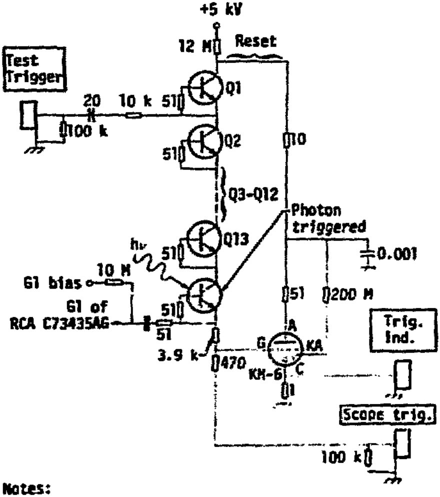
Thomas - Fig. 5



Notes:

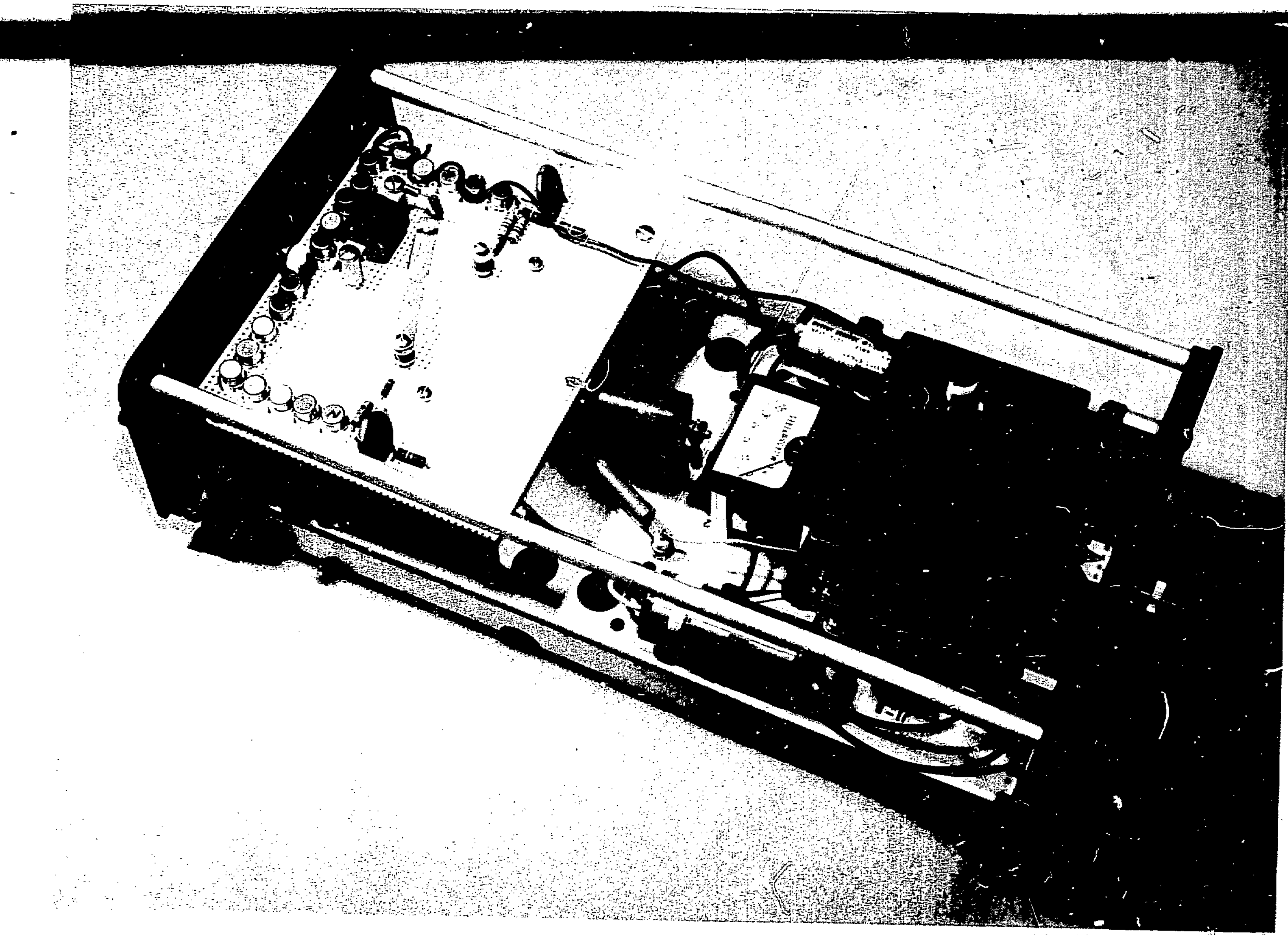
1. C5 adjusts sweep time
2. Q1-Q20 are 2N3700

Thomas - Fig. 6



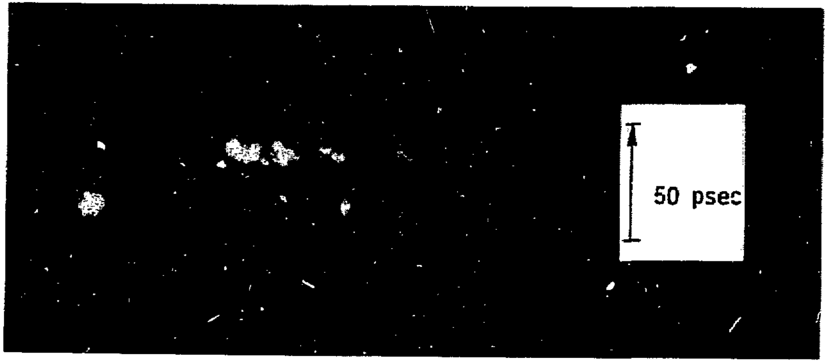
Notes:
1. Q1-Q14 are 2N3700

Thomas - Fig. 7

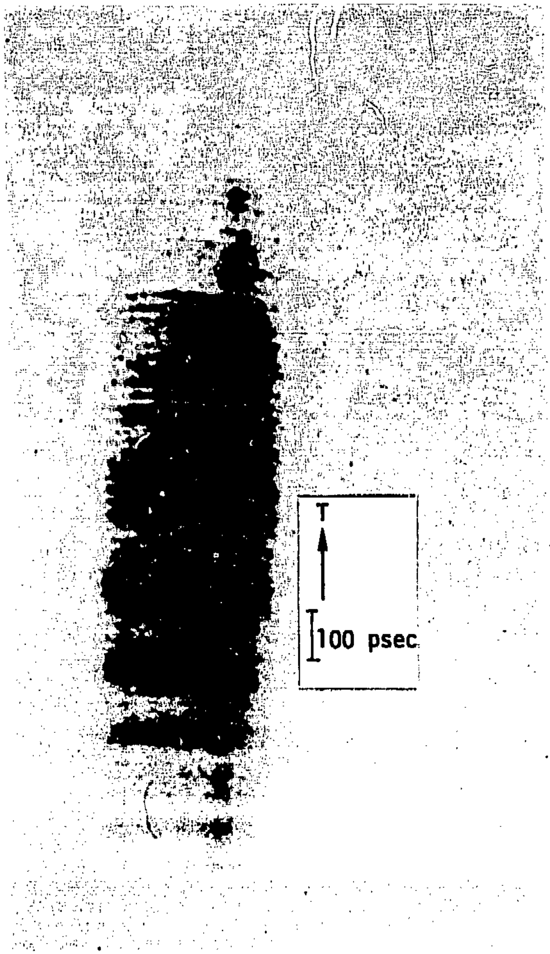


Thomas - Fig. 8

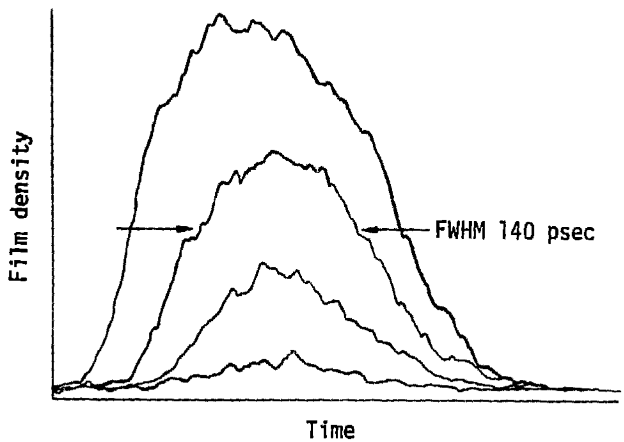
Thomas - Fig. 9



Thomas - Fig. 10



Thomas - Fig. 11



Thomas - Fig. 12