SWEEP DEVICES FOR PICOSECOND IMAGE-CONVERTER STREAK CAMERAS [*]

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ABSTRACT

Four different sweep devices based on microwave tubes, avalanche transistors, krytrons, and laser-triggered spark gaps are treated in detail. These control circuits are developed for picosecond image-converter cameras and generate sweep pulses providing streak speeds in the range of 10^7 to 5×10^{10} cm/sec with maximum time resolution better than 10^{-12} sec. Special low-jitter triggering schemes reduce the jitter to less than 5×10^{-11} sec. Some problems arising in the construction and matching of the sweep devices and image-streak tube are discussed. Comparative parameters of nanosecond switching elements are presented. The results described can be used by other authors involved in streak camera development.

INTRODUCTION

Application of image-converter techniques (1, 2) in quantum electronics reveals the remarkable efficiency of the streak camera due to its high temporal and spatial resolution, large spectral and input intensity range, possibility of instant recording of single-shot events with practically negligible delay and very small jitter. Image-converter streak cameras (ICSC) have now overcome the picosecond limit and are still moving towards the femtosecond goal.

Allthough progress in picosecond streak camera development depends mainly on the image-converter tube (ICT) itself, the question arises of how efficiently these ultimate tube performances may be used. It is well known that a very important part in good ICT performance is played by the pulse-control circuit .

In this report we wish to present various sweep devices developed for pulsed operation of picosecond ICSC and to investigate some problems arising in the design and matching of these sweep circuits with time-analyzing image tubes.

MAIN REQUIREMENTS FOR PULSE CONTROL CIRCUIT DESIGN

Almost all known ICTs used in picosecond streak cameras have capacitor type deflection systems (3-10). The only exceptions are PIM-3-SMV (UMI-93M) type tubes (11) which have a symmetrical 3 GHz-bandwidth strip-line deflection system of 75 Ω impedance.

With such a system the slit image can be deflected over the complete screen in (1-2) × 10^{-10} sec and the problem is to generate two symmetrical deflection pulses of suitable rise time and 1.5 kV amplitude. This means that from the control circuit an output pulse current of up to 20-40 A is necessary.

The capacitor type deflection system on the other hand can be treated as an equivalent resonant circuit with the capacitance and inductance arising respectively from the deflection plates and connection leads (12). The resonant frequency of such an equivalent circuit lies in the 150-350 MHz range, and hence the minimum rise time of the deflection voltage which can be applied to the system is (1-2) × 10^{-9} sec. The corresponding streak duration is the same.

Now if we assume that along the streak axis about 200-500 resolvable elements can be recorded, the best time resolution, defined only by the streak velocity, approaches (0.2-1) × 10^{-12} sec for the 3 GHz deflection system, and (0.2-1) × 10^{-11} sec for the capacitor type system. The corresponding maximum streak speeds will be about 5×10^{10} and 5×10^{9} cm/sec respectively. It should be mentioned that there is at least a factor 2-4 in the streak velocity to be gained by overpulsing of the deflection system, as well as another factor 2-3 by further improvement of the deflection system frequency response.

The estimates given for two types of deflection system show that picosecond time resolution can be reliably obtained with ICT's possessing capacitor type plates (13). Application of the strip-line deflection system is justified only for femtosecond ICSC. Obviously it is useless to employ a strip-line system if the sweep-generator is unable to produce deflection pulses of rise time less than 10^{-9} sec. If circumstances require separate construction of the control circuit and the tube, or connection of more than one tube in series to the same control circuit, the only solution is to use the impedance matching cable line (14). In this case application of the strip-line deflection system is preferable.

On the basis of the above considerations it may be concluded that, independently of the type of deflection system, any picosecond streak camera should be supplied with a nanosecond control circuit able to provide deflection pulses of up to 3-4 kV in overall amplitude with a nanosecond rise time or less. Other very important requirements in pulsed circuitry for picosecond ICSC are as follows :

1. For picosecond camera triggering it is desirable to have both electrical and optical inputs. In the case of electrical triggering the required amplitude of the input pulse should not exceed a few volts. With light triggering, the required energy should usually be in the nanojoule to microjoule range.

2. In order to shorten the optical delay to a reasonable length of 2-4 meters (which is specially important for the ICSC triggered by the process under investigation), the control circuit delay T has to be around 10^{-8} sec or less.

3. The jitter ΔT should be at least 5-10 times shorter than the maximum streak duration, thus within the range 10^{-10} - 10^{-11} sec depending on streak velocity.

4. In order to prevent image deterioration and improve dynamic spatial resolution two symmetrical, well-balanced deflection pulses have to be generated.

5. Since the streak deflection pulses are usually generated by passive RLC-integrators it is rather difficult to have streak nonlinearities below 5-10 %. A possible solution is to generate deflection pulses of greater amplitude and use only their linear portion.

EXPLORATION OF NANOSECOND HIGH-CURRENT SWITCHING ELEMENTS

The above requirements show the real difficulties encountered in designing sweep circuits for picosecond ICSC. The main problem in this case is reduced to finding very stable, high pulse-current, nanosecond switching elements. Tables I and II give the main parameters of some elements tested and used by the authors in the construction of the various streak circuits presented below.

From Table I it can be seen that avalanche transistors produce pulse currents from 0.5 to 2 A with $(1-2) \times 10^{-9}$ sec rise time. This means that they can be employed in pulse preshaping circuits being loaded by low-resistance impedance. Furthermore, avalanche transistors when connected in series can deliver complete output sweep pulses for capacitor type deflection systems with currents of 7 to 15 A. The full high voltage transition so obtained is limited to 1.5×10^{-9} sec or greater rise time.

Pulse currents of tens of amperes for output stages of sweep devices matched with low-impedance deflection systems can be delivered by power-beam microwave triodes developed for pulse operation (see Table II). The frequency response of the microwave tubes is high enough (up to 3-5 GHz) to generate pulses with (1-3) x 10^{-10} sec rise time. However if the shaping circuit is formed by avalanche transistors, the minimum rise time of the output pulses barely reaches (1-2) x 10^{-9}sec. In any case owing to high stability and negligible jitter the microwave power tubes can be successfully used to generate deflection pulses for both distributed and capacitor type deflection systems.

As to krytrons (Table II) they can easily provide pulse currents of 80 - 100 A in a low impedance load with 10^{-9} sec rise time. Thus a very simple circuit can be designed for any type of deflection system. Unfortunately the wide application of krytrons for picosecond control circuits is limited by their triggering instabilities and limited life.

Currents of over a hundred amperes with subnanosecond rise time can be obtained reliably with laser-triggered spark gaps (LTSG). The latter have a nanosecond delay time and jitter about 10^{-9} sec. Such jitter however is not acceptable for control circuit construction if the ICSC is intended for single-event measurements on the picosecond to femtosecond range.

Recently new approaches were tried successfully in the development of switching elements for generation of electrical pulses with less than 10^{-9} sec rise time. First experiments on electron bombarded semiconductor device (15) indicate a possible attainment of 5 x 10^{-10} sec rise time pulses of one hundred volts amplitude.

Another recently reported way (16, 17) of shaping subnanosecond high voltage-pulses was based on the application of a microstrip transmission line generator controlled by a picosecond laser pulse. Efficient switching action was obtained with only a few microjoules of input laser energy creating a high density electron-hole plasma at the surface or in the bulk of the microstrip substrate (silicon, GaAs, ZnO or other structures). In this way electrical pulses of up to 1 kV with rise time corresponding to the light pulse duration (i.e. up to 10^{-11} - 10^{-12} sec) can be produced.

In the following sections it will be shown how some of the above-mentioned active elements were used in the design of sweep devices for picosecond ICSC.

SWEEP CIRCUIT BASED ON AVALANCHE TRANSISTOR AND MICROWAVE TRIODES

Figure 1 shows the electrical diagram of a sweep device based on avalanche transistors and high frequency metal ceramic microwave triodes.

The circuit contains a pulse generator using two 2N3700 transistors. The 15 nF capacitor and the delay line connected respectively to the collectors of Q_1 and Q_2 are charged to the power supply voltage which is adjusted near the avalanche threshold of the transistors.

The triggering pulse is applied to the base of Q_1 through a ferrite toroidal transformer TR1 described later in the text.

The avalanche of Q_1 induces the avalanche of Q_2 and discharges in serial mode the capacitor and the 50 Ω delay line. The 200 V pulse thus obtained, is sufficient to drive a high frequency EIMAC 8755 Metal Ceramic triode, increasing the pulse amplitude to 700 V. In turn, this pulse, after polarity inversion by a wide band width transformer TR2, is applied to the grid of a Thomson-CSF TH 318 type high power microwave triode. A double winding, wide band width transformer TR3 of 150 Ω input impedance is connected to the plate of the TH 318 triode.

This transformer has two 75 Ω outlets, each connected to the appropriate input of the symmetrical stripline deflection system.

At the triode maximum pulse current of about 2 A, the two symmetrical streak pulses have a 1.6 kV amplitude and 2.5×10^{-9} sec rise time.

The transformer, TR3, is made by winding two standard 75 Ω cables together through 4 ferrite cores. The cores have 31 mm external diameter, 18.5 mm internal diameter, 7 mm width, and an initial permeability of 2000. The transformer, TR2, uses a single 75 Ω coaxial cable winding on the same type core. TR1 consists of three turns of two standard Teflon insulated "wire wrap" wires, wound together, to obtain maximum coupling coefficient, on a LTT FERMALITE 1105, 10 mm internal diameter core.

Information for the design of such a wideband transformers can be obtained in (26).

It is convenient to obtain two sweep rates, one fast and one slow by switching the length of the delay cable in the collector of transistor Q_2, and the passive RLC integrator in the anode of V_2, simultaneously.

This switching is performed by magnetically actuated, reed relays MC1, MC2, MC3, MC4, which are rated at 7.5 kV operating voltage.

If more than two rates are necessary, plug in modules composed of delay line, switches, and RLC modules are necessary. In designing the RLC integrators, an RC time constant in accordance with the sweep rate was choosen.

The peaking inductance L, necessary only for the fastest sweep rates was adjusted by "cut and try" in order to obtain the best compromise between linearity and oscillation damping.

Basis for the calculation of this sort of circuit can be obtained in (27).

The length of the Q_2 delay line is adjusted to obtain one "to and fro" of the pulse in a time corresponding to the total duration of the sweep.

A sweep range from 2.5 nsec to 200 nsec has been obtained, and the overall non-linearities are less than 15 %.

AVALANCHE TRANSISTOR CIRCUITRY

Sweep circuitry based on avalanche transistors connected in series with photon triggering was first reported in (18). Later on such a circuit was successfully used in the commercial Thomson-CSF type TSN-503 streak camera (19). This type of sweep device is quite compact. It has low power requirements, small delay and jitter, and streak speeds up to 3×10^9 cm/sec can be easily achieved.

The authors have designed a circuit based on faster transistors, increasing the streak speed to 5.5×10^9 cm/sec, for up to 4 cm useful streak length corresponding to a linear deflection voltage of 2 kV. By the use of a tunnel diode in the triggering device the jitter was decreased to 3.10^{-11} sec. Fig. 2 presents the electrical diagram of the sweep voltage generator built up with 24 avalanche transistors. By discharging the capacitance of the deflection plate circuit through the transistor chain, two symmetrical deflection pulses were formed. Additional LC-shape modules installed in parallel with the capacitance of the deflection plates can be used to decrease streak velocity.

Triggering was achieved by applying an electrical pulse through a wide band transformer. This pulse drives two transistors which cause all 24 components to be avalanched. At 1 V triggering level and 7 nsec rise time the circuit delay is about 5 nsec.

In order to ensure an even distribution of potential in the avalanche chain, transistors of equal avalanche voltage around 170 V were carefully selected. The output sweep pulse across the deflection plates had a maximum amplitude of 4 kV with a rise time of 1.5×10^{-9} sec. Sweep nonlinearities were less than 5 % (Fig. 5). The sweep circuitry described can operate at a maximum repetition rate of 1.5 kHz.

The simplicity and reliability of this sweep device justify its application for the capacitor type deflection system whenever a maximum streak speed of less than 5×10^{9} cm/sec is acceptable.

AVALANCHE TRANSISTOR-KRYTRON SWEEP DEVICE

The application of krytrons for generating 4-5 kV sweep pulses with rise times as low as 10^{-9} sec offers a good alternative to all other switching elements due to the krytron's small size and its negligible power consumption. The first announcement on krytron application for streak cameras (8) indicated that streak speeds of up to 10^{10} cm/sec can be obtained.

This section describes a modified krytron circuit with keep-alive pulsing and stable dc-voltage power supply (see Fig. 3). A 100 V pulse from a low-jitter triggering unit is applied to the driver through a constant Z-attenuator. The generator consists of four avalanche transistors and provides, at the output of the matching transformer, a very sharp 1 kV-pulse which feeds the krytron grid. Before the grid pulse arrives a pretriggering unit, consisting of a slow-switch transistor and a preionization level set-up, generates an extra current of 0.6 mA during one millisecond into a krytron keep-alive electrode. Such preionization of the krytron leads to a noticeable decrease in the delay (down to ten nanoseconds instead of 40 nsec as specified in the technical data), but reduces the life-time of the unit if the value given is exceeded.

The krytron circuit generates, for the capacitor type deflection system, a pulse of 10^{-9} sec rise time and up to 4.5 kV amplitude. Timing resistors and integrating disk capacitors in plug-in modules allow changing streak speeds. Maximum streak velocity was 7×10^{9} cm/sec.

Some additional experiments to minimize the krytron circuit jitter were conducted. It was discovered that if dc plate and keep-alive potential instabilities were reduced to 0.01 % the krytron jitter decreased to $(5-10) \times 10^{-11}$ sec.

The prolonged use of a krytron sweep circuit confirms its reliability during 3-4 months of 8 h a day operation triggering occuring one time each minute. After this period the delay time and jitter can be slightly degraded.

Thus by periodic replacement of the krytron element, very reliable experimental conditions can be guaranteed.

DEFLECTION CIRCUIT BASED ON LASER-TRIGGERED SPARK GAP (LTSG)

The first application of high-pressure nitrogen LTSG's for streak pulse generation was reported in (20). Immediately this first application advanced the fastest known streak velocity to 1.4 × 10^{10} cm/sec. In the present paper the most advanced modification of the LTSG symmetrical deflection circuit is discussed. This is capable of generating streak speeds up to (5-10) × 10^{10} cm/sec (Fig. 4). At a light triggering level of less than a millijoule the jitter was reduced to (0.5-1) × 10^{-9} sec with a maximum overall circuit delay of the order of 10^{-8} sec. The system provides two pairs of symmetrical outputs : one pair for the 3 GHz stripline deflection system and the other for the shutter and accelerating grid systems. The accuracy in arrival time of the deflection pulses at the plates lies within a few picoseconds. The overall bandwidth of the deflection device including LTSG, cables and the deflection plates themselves is in the 2.3 GHz region.

Streak velocity selection was accomplished by variation of the high power supply voltage, thus providing adjustment over a range of 2-3 times. Additional streak speed adjustment was provided by modification of the gap width and pressure tuning. Hence for this particular circuit the streak speed ranged between 1.5 × 10^{10} and 5 × 10^{10} cm/sec.

The possibility of simple production of high-voltage, subnanosecond electrical pulses with the help of the LTSG circuitry has made such devices very useful for subpicosecond cameras. The main drawback of the LTSG is its noticeable jitter. In order to increase the probability of recording single picosecond phenomena it is necessary to multiply the number of pulses by optical means.

LOW-JITTER TRIGGERING DEVICES

As mentioned earlier, for picosecond cameras the jitter has to be about 10^{-10} sec or less. Such a value is easily obtained with microwave tube circuitry. Direct optical triggering through the p-n junction of avalanche transistors also gives jitter of this magnitude and requires nanojoule input level. Jitter was further reduced using the two circuits described below.

The first circuit, described in detail by CUNIN et al. (21), is based on a tunnel diode characterized by a subnanosecond intrinsic rise time. The tunnel diode switching speed is mainly related to its peak and bias current, as well as to the width and amplitude of the incoming pulse. By choosing a low capacitance (about 5 pF) tunnel diode with a peak current of 50 mA the intrinsic switching time was established at the 5×10^{-11} sec level.

The triggering circuit consists of two separate parts : the time sequence generator with associated logics and the tunnel diode triggering unit itself. The time sequence generator is initiated by the laser flash lamp and produces, for each new laser shot, a nominal diode bias current independent of laser output energy variations. This generator also puts the tunnel diode into its monostable mode. At a triggering pulse level of 50 mV and 5×10^{-10} sec rise time, the delay of the circuit itself is about 7×10^{-9} sec and jitter less than 3×10^{-11} sec for a five times variation of the input laser signal. The triggering circuit generates a very stable negative output pulse of 5 V amplitude and 1.5×10^{-9} sec duration. This pulse can be applied to trigger any of the above-described control circuits.

The second triggering device contains a fast 0.2×10^{-9} sec rise time photodiode (RTC type XA-1003) perfectly matched to the avalanche transistor shaping circuit (Fig. 6). All dc supply voltages for the circuit are stabilized to within 0.01 %. A 100 V, 5×10^{-10} sec rise time pulse is provided at the output of this triggering device.

For a 2-3 times change in input light intensity, the overall jitter of the device does not exceed 5×10^{-11} sec. This small jitter was demonstrated by displaying on one photograph eleven successive laser shots at different input power levels (Fig. 7). Each trace shows the temporal behaviour of two 30 psec Nd-glass laser pulses separated by 100 psec. From this picture one can verify the very stable position of the recorded pulses on the time axis. The qualities of this triggering device such as simplicity, reliability and very small jitter are thus very useful for the design of commercial picosecond streak cameras.

All the characteristics of the sweep and triggering devices developed by the authors and described here are summarized in Table III.

On the basis of the data presented above, some criteria can be established for the type of deflection device to choose for a particular picosecond ICSC. It is obvious that from the point of view of simplicity and reproducibility the use of avalanche transistor circuitry alone is quite acceptable for reasonable streak linearities and speeds. Microwave tube circuitry needs more skill and experience but the circuit has the major advantage of very high stability and reliability, which together with cable-matched load facilities allows connection of more than two image tubes in series for simultaneous or delayed recording.

The krytron circuit offers many advantages even though it needs very stable power consumption and the krytron itself has to be replaced quite frequently. Further modification of such circuitry in symmetrical configuration could probably improve streak linearity and dynamic spatial resolution.

Sweep devices based on nitrogen LTSG are still the fastest, but their application for recording of single picosecond processes requires an optical multiplying system due to the jitter which is comparable to the minimum streak duration. Another approach was demonstrated by SUTPHIN et al. (22) by a 7×10^{-11} sec jitter LTSG design with a thin solid dielectric. Such a spark gap provides less than 5×10^{-10} sec rise time for the 10 kV pulses used for gating and streak operation of the picosecond ICSC.

In conclusion it is worth repeating that simple, reliable and fast sweep circuitry design will obviously facilitate quantitative picosecond measurements of transient phenomena.

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FIGURE CAPTIONS

Fig. 1 - Avalanche transistors - microwave triode deflection device.

Fig. 2 - Series connected avalanche transistor circuitry.

Fig. 3 - Avalanche transistors-krytron deflection circuit.

Fig. 4 - LTSG sweep device.

Fig. 5 - Curves of linearity, describing the avalanche transistor sweep circuit.

Fig. 6 - Photodiode-avalanche transistor triggering unit.

Fig. 7 - Eleven successive shots demonstrating the triggering jitter.

TABLE I - AVALANCHE TRANSISTORS

Company	Type	Collector supply voltage (V) R_c = 300 KΩ	Emitter pulse current (A)		Output pulse (V) R load 75 Ω		Rise time (nsec)	Fall time (nsec)
			Charge line Z = 75 Ω	Charge cap. C = 100 pF	Charge line Z = 75 Ω	Charge cap. C = 100 pF		Charge line
1	2	3	4	5	6	7	8	9
CERMEX	CX1116	200	≤ 1	≥ 1.5	70	150	0.7-0.8	2
FAIRCHILD	2N3641	250	0.45	0.9	30	60	0.8-0.9	1.1-1.2
MULLARD	BSX61	160	0.75	1.1	50	80	0.8-0.9	2 -2.5
MOTOROLA	2N5271	250	1	2	75	150	1.2-1.4	2.5
MOTOROLA	2N5681	320	1	2	75	150	1.5-1.7	1.9-2.1
RAYTHEON	RT3333	250	1	2	75	150	1.4-1.6	2 -2.5
FAIRCHILD or NATIONAL	2N3700	250	1	2	75	150	1.5-1.7	2 -2.5

TABLE II – HIGH CURRENT SWITCHING ELEMENTS

Type of device cut-off frequency reference	Filament power consumption U_F(V) I_F (A)	Cut-off frequency (GHz)	Inherent capacitance (pF)	dc plate voltage (KV) Grid bias voltage (KV)	Plate pulsed current (A) Grid pulsed current (A)	Grid positive pulse (V)	Average grid and anode dissipation (W)
1	2	3	4	5	6	7	8
EIMAC 8755							
Microwave	6.3		$C_{IN} = 9.5$	8	7.5		1.5
Metal-ceramic		3	$C_{OUT} = 0.06$			80-100	
Planar triode (23)	1.3		$C_{GP} = 1.0$	-(0.12-0.15)	1		150
THOMSON-CSF							
TH-318							
Microwave	6.3		$C_{IN} = 15$	6.2	20		3
Metal-ceramic		1.5	$C_{OUT} = 0.1$			120	
Planar triode (24)	5.5		$C_{GP} = 8.5$	-(0.15-0.2)	4		700
EG & G							
KN-22	Triggering				80-100		Keep-alive
Krytron (25)	Delay 40 ns	–	1-2	0.4-7		750	Current 0.3 mA
	Jitter 5 ns				0.1-1		Number of total firing 2. 10^7
Laser triggered spark gap (20)	Triggered Delay 2 ns Jitter 0.5 ns	2.3		10-40	100-300	Fractions of millijoules photonic energy	Number of total firing $\sim 10^4$

TABLE III – SWEEP DEVICES DEVELOPED BY THE AUTHORS

Type of sweep circuitry	Sweep range (cm/sec) Maximum streak resolution (sec)	Streak length (cm) non-linearities (%)	Delay time and jitter (sec)	Triggering pulse (V) Rise time (sec)	ICT type and deflection system description	Maximum streak repetition rate (Hz)
1	2	3	4	5	6	7
Avalanche transistor and microwave metal-ceramic triodes	$2.5\times10^{7}-2\times10^{9}$ 5×10^{-12} at $10\frac{LP}{mm}$	5 10	1.5×10^{-8} 2×10^{-10}	1 10^{-8}	UMI - 93M 75 Ohm distributed type	50
Series connected avalanche transistors (12x2 components)	5×10^{9} (fixed) $(2-4)\times10^{-12}$ at $(5-10)\frac{LP}{mm}$	5-7 10	1.1×10^{-8} 3×10^{-11}	> 0.05 5×10^{-10}	P-856 Capacitor type	1 500
Avalanche-transistors and krytron	5×10^{9} (fixed) $(2-4)\times10^{-12}$ at $(5-10)\frac{LP}{mm}$	5-7 10	5×10^{-9} 5×10^{-11}	1 10^{-8}	P-856 Capacitor type	50-100
Laser-triggered spark gap	$1.5\times10^{10}-5\times10^{10}$ 5×10^{-13} at $4\frac{LP}{mm}$	5 10	$(5-8)\times10^{-9}$ 5×10^{-10}	Fraction of millijoules photon energy	UMI - 93M 75 Ohm Distributed type	1-10

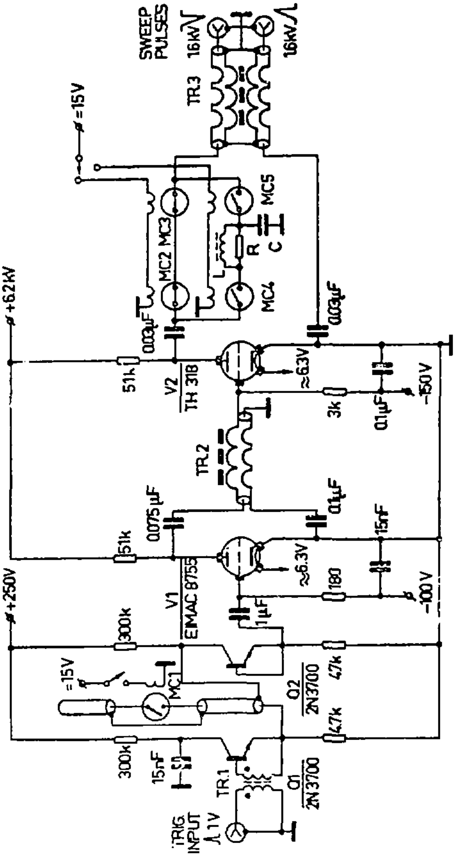
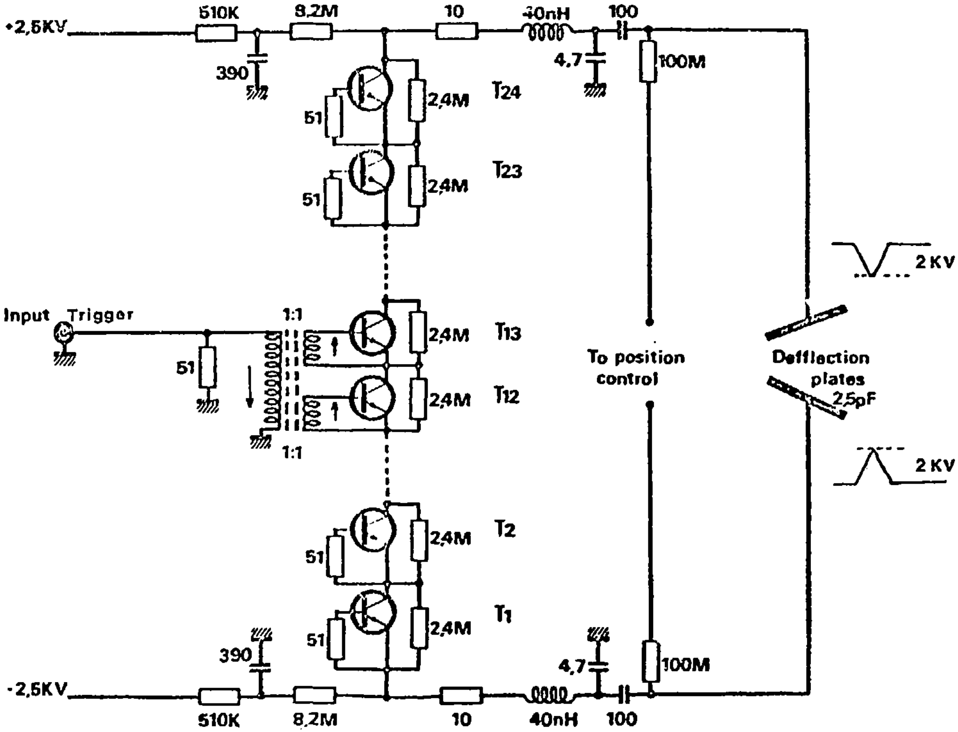
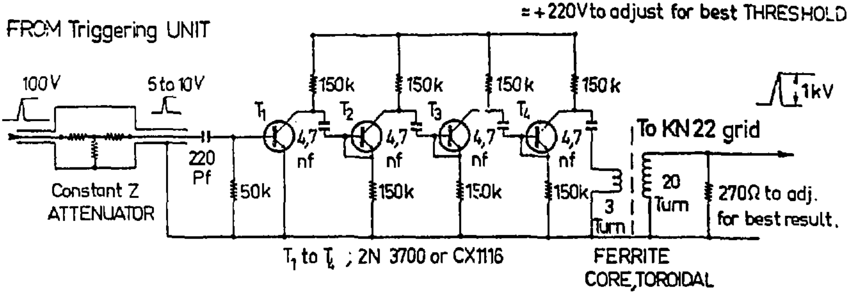

TRIG INPUT 1V
TR.1
Q1 2N3700
300k
15nF
=15V
MC1
Q2 2N3700
47k
47k
300k
+250V
V1 EIMAC 8755
1µF
180
≈6.3V
−100V
15nF
51k
0.075µF
0.1µF
TR.2
51k
V2 TH 318
3k
0.1µF
−150V
≈6.3V
0.03µF
+6.2kV
MC2 MC3
MC4
MC5
L
R
C
0.03µF
=15V
TR3
SWEEP PULSES
16kV
16kV

Fig 1

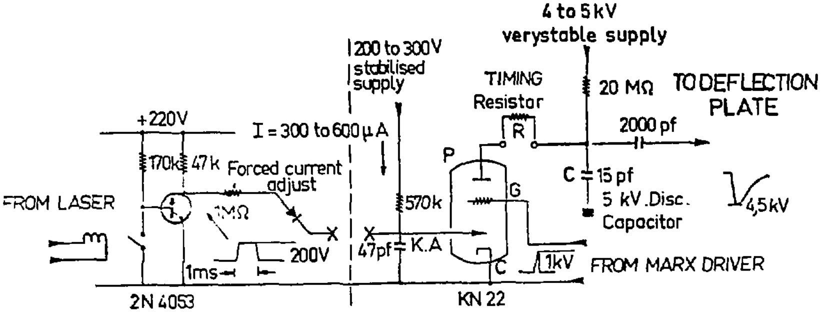
Fig 2



T1-T24: CX1116



MARX AVALANCHE DRIVER



OPTIONNAL PRETRIGER UNIT
(Reduction of delay)

KRYTRON TIME BASE

Fig 3

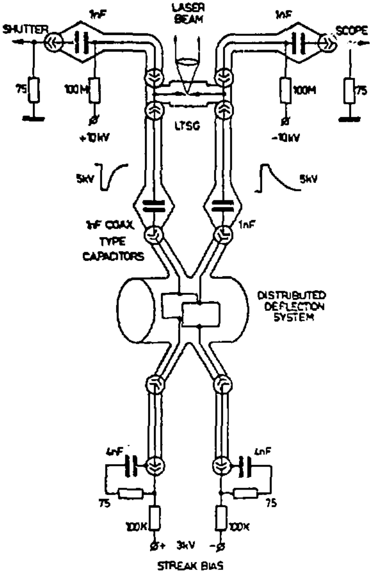
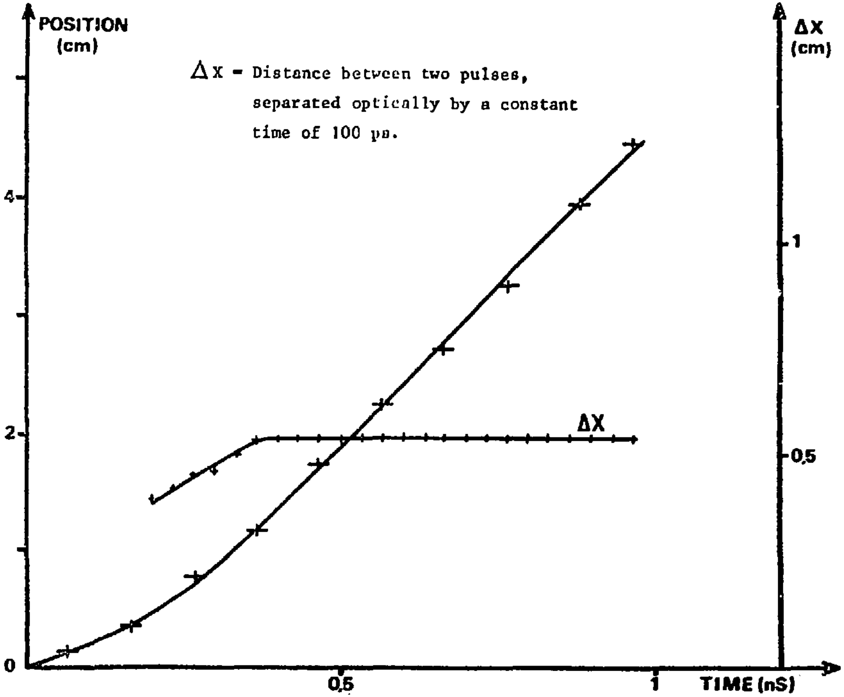
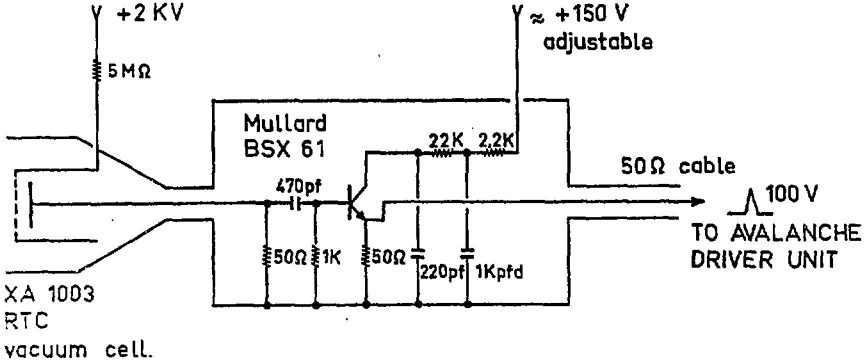

LASER BEAM
1nF
1nF
SHUTTER
SCOPE
75
100M
100M
75
LTSG
+10kV
-10kV
5kV
5kV
1nF COAX TYPE CAPACITORS
1nF
DISTRIBUTED DEFLECTION SYSTEM
4nF
4nF
75
75
100K
100K
+ 3kV -
STREAK BIAS

Fig 4

Fig 5



ΔX = Distance between two pulses, separated optically by a constant time of 100 ps.



TRIGGERING UNIT

Fig. 6

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