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TITLE ULTRAFAST GATING OF PROXIMITY-FOCUSED MICROCHANNEL-PLATE INTENSIFIERS

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Ultrafast gating of proximity-focused microchannel-plate intensifiers

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Abstract

Proximity-focused, microchannel-plate (MCP) image intensifiers have been used at Los Alamos for many years to allow single frame film and video exposure times in the range of 2.5 to 10 ns. There is now a program to reduce gating times to <1 ns. This paper reviews previous work and the problems in achieving good resolution with gating times of <1 ns. The key problems involve applying fast electrical gating signals to the tube elements. We present computer modeling studies of the combined tube, tube connection, and pulser system and show that low photocathode surface resistivity must be obtained to permit fast gating between the photocathode and the MCP input. We discuss ways of making low-resistivity [illegible] photocathodes, using gallium arsenide photocathodes, and various means of gating the tubes. A variety of pulser designs are being experimentally evaluated including spark gaps, avalanche transistors, Krytron tubes with sharpening gaps, step recovery diodes, and photoconductive elements (PCEs). The results of these studies are presented. Because of the high capacitances involved in most gating schemes, the tube connection geometry must be of low-impedance design, and our solution is presented. Finally, ways of testing these high-speed camera systems are discussed.

Introduction and History

A proximity-focused image tube was first described by Holst et al.[1] in Germany in 1934. Subsequent developments in photocathodes, phosphors, vacuum technology, and fiber optic faceplates have made such diode intensifiers reliable and effective devices although their gain is limited to approximately 30 in single-stage designs. The continuous dynode electron multiplier suggested by Farnsworth[2] in 1930 led to the development of MCP electron multipliers at Bendix Research Laboratories about 1960. Incorporation of an MCP multiplier in the basic proximity-focused diode intensifier has made possible small, rugged intensifiers with luminous gains near 10,000. This technology has been developed primarily for military night vision devices, culminating in the present generation III wafer tubes.[3-5] Major credit for this development must go to the US Army Night Vision Laboratory and its contractors, although significant work has also been done in England, France, and the Soviet Union. The literature on MCPs is extensive but not easily found by neophytes. References 6-12 give a good introduction. Very extensive coverage was given in Acta Electronica, Vol. 14 (1&2) (January and April 1971) and Vol. 16 (1) (January 1973) and in the proceedings of the Imperial College Photoelectronic Image Devices Symposia published in Advances in Electronics and Electron Physics. While developed for image intensification, MCPs are also directly sensitive to energetic photons and charged particles and thus are frequently used in space physics and nuclear science. Their superior time resolution has led to their use in fast photomultiplier tubes. They are also used for electron amplification behind the phosphor screens of high speed oscilloscopes.

Use of proximity focused diode image intensifiers in high speed photography was reported beginning in the late 1960s with the Laboratoires d'Electronique et de Physique appliquee at Limeil Brevannes, France, developing tubes capable of 100 ps gating.[illegible] In the early 1970s, the gating of proximity-focused MCP intensifiers was reported.[illegible] Later work including many applications is discussed in Ref. [illegible].

In 1971, Lieber[24] and co-workers at Los Alamos demonstrated 4-ns [illegible] gating time using 18-mm diam MCP tubes. Based on this work, four basic types of cameras [illegible] have been built at Los Alamos in the last decade. Key characteristics are given in Table 1.

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Table 1. Los Alamos MCP Camera Systems

Tube Diameter	Shortest Practical Gating Time	Output Media	Principal Developers	References
18 mm	2.5 ns	vidicon tube	Group P-15	33
25 mm	10 to 20 ns	vidicon tube	Group P-15	--
25 mm	5 to 10 ns	35 mm (Electric film advance)	Group P-14	--
40 mm	10 to 15 ns (offers multi pulsing capability	70 mm (4" x 5" film)	Groups M-3, E-7, & M-7	34 (pulser only)

Over 75 cameras have been built at Los Alamos, and several of the 40-mm cameras were built for other organizations. The basic performance specification for all the cameras is a resolution of 10 to 15 line-pairs/mm with luminous gains between 3000 and 10,000 for S20 photocathodes and P20 phosphors. All tubes discussed here are the "wafer" type, which implies double proximity-focusing (proximity focused between photocathode and MCP input as well as between MCP output and phosphor). Several variations have been used or tested including S25 and GaAs photocathodes, P-11 phosphors, and operating the tubes in series with diode intensifiers to obtain higher gain. With the exception of the GaAs photocathode tubes, nearly all tubes have been generation II, ITT types F-4111 (18 mm), F-4112 (25 mm), or F-4113 (40 mm)[35] specified for pulsed operation. Figures 1 and 2 are pictures of these tubes, and Fig. 3 is a cross-sectional drawing. The pulsers have been avalanche transistor circuits. These camera systems are generally reliable and have obtained data for many Los Alamos studies.

There are many applications where gating times of <1 ns would be advantageous, and we hereby report our efforts to achieve this.

Gating schemes

There are four possible ways to gate an MCP wafer tube.

1. Photocathode gating

The voltage between the photocathode and the MCP input is switched (Fig. 4), requiring the smallest voltage swing ([illegible]200 V for generation II tubes), but presenting a moderately high capacitive load. If the voltage swing is not great enough, or if there are slow risetimes and falltimes, a defocus condition results. A shutter ratio (ratio of light gain in "on" state to "off" state) of [illegible] is usually achieved, and all our work is based on this mode.

2. MCP gating

The gating voltage is applied directly to the MCP, again driving a moderately high capacitive load, and the voltage swing required is larger ([illegible] V). Because the overall tube gain is approximately proportional to the [illegible] power of the MCP voltage, the light response will have faster risetimes and falltimes than will the electrical driving pulse. The tube gain during the gate pulse will be very sensitive to the gate pulse amplitude. There is no change in focus as the tube is gated. Problems may arise during fast gating in getting the MCP to charge uniformly as a function of both thickness and radius. Because the instantaneous gain is such a strong function of MCP voltage, any nonuniformities as the gating pulse propagates inward from the edge are magnified. Unless one can achieve very fast propagation times, the "hollow center" problem (the tube turning on only on the edge when driven with a fast pulse) will be severe. Fast propagation depends on low surface resistivities and low dielectric constants. The reported[10] shutter ratio for MCP gating is [illegible] 10^4, a further disadvantage.

3. Phosphor gating

The gating pulse is applied between the MCP output and the phosphor. The capacitance that must be driven is much lower, but the voltage swing is several thousand volts. Because the gate pulse energy required is so much higher, this mode is usually not considered. One probably can obtain fairly high shutter ratios

4. Combined MCP-phosphor gating

An MCP wafer tube can also be gated by driving the MCP input and the phosphor with a single pulse. The spacings and the dielectric constant of the MCP are such that a single pulse can be made to capacitively divide voltage appropriately between the MCP and the phosphor gap. Again, because the gate pulse energy required is high, this mode is not usually considered.

The limits on gating speed of proximity focused diode intensifiers were discussed in 1970[19] and 1971[21] by Clement et al. and stated to be ≈100 ps. Similar limits, electron transit time, gating signal shape, and photocathode and MCP input face electrode resistivity apply to MCP wafer tubes using photocathode gating. In the Los Alamos cameras, the electron transit time for a full voltage gating pulse of 180 V is ≈65 ps. Thus the dominant limiting effects are the gating signal shape and the electrode resistivity. Gating signal shape is defined by the gate pulse generator and its connection to the tube electrodes. The electrode resistivity controls both the propagation velocity and the spreading of the gating pulse as it propagates from the edge of the tube to the center. Some work[19,21] has been done with tubes representing a section of a uniform parallel strip transmission line, an effective implementation that conceptually simplifies the analysis. However, to achieve the desired <1-ns gating with minimal re-engineering of the tubes, we plan to drive them at up to four points around the circumference, and in our analysis, we model the tube as a radial transmission line with a wavefront propagating inward from the circumference to the center. Others have analyzed this configuration using a distributed resistive-capacitive model.[36-38] This earlier work, while providing an accurate analysis of the R-C model, did not allow simultaneous modeling of the pulser, the connections between the pulser and the tube, the edge geometry of the tube, or the inductance of the tube.

The System Model

Our electrical engineering background led us to use a lumped constant model and NET-2, a computer network analysis program,[39] that readily allows consideration of all the noted features and complete system evaluation of the electrical performance.

Figure 5 is our electrical model of the tube. For 18-mm tubes, the photocathode-MCP input face section is divided into a series of nine 1-mm-wide concentric rings, and six more sections represent the tube edge geometry. The electrical properties of each section are defined by the following equations:

$$C_{ab} = \frac{\pi\epsilon_0}{d}\left(b^2 - a^2\right)$$

$$L_{ab} = \frac{\mu_0 d}{2\pi} \ln b/a$$

$$R_{ab} = \frac{R_s}{2\pi} \ln b/a$$

C_{ab} is the capacitance in farads between the photocathode and the MCP input face in the region of a concentric ring of inner radius a meters and outer radius b meters.

ϵ_0 is the permittivity of free space, the vacuum between the surfaces, (8.85×10^{-12} farads/meter).

d is the separation between the photocathode and the MCP input face in meters.

L_{ab} is the inductance in henries between r = a and r = b of a parallel plate radial transmission line consisting of the photocathode and the MCP input face.

μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ henries/meter).

R_{ab} is the resistance in ohms between r = a and r = b consisting of the sum of the resistances of the photocathode surface and of the MCP input face.

R_s is the sum of the sheet resistance of both the photocathode and the MCP face in ohms/square.

The edge regions of the tube are defined by the same equations using new values for d where the spacing tapers. For C_{ab} in the insulator region, multiply by the dielectric

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constant of the ceramic (8.9). On the ITT tubes, over half the tube capacitance is due to the ceramic insulator region. Table 2 gives the values of each circuit element in Fig. 5 for an 18-mm tube as a function of spacing and surface sheet resistances. In the actual tube, the inductances and resistances are distributed on both sides of the line, but for analysis they can be lumped on one side. This does not affect the validity of the model.

Table 2. Component Values for Tube Model (Fig. 5)

Region (outer to inner radius) (millimeters)	L (picohenries)	C (picofarads)	R (ohms)
Insulator region: (15.2 to 13.7)	L1A = 9.1	C1A = 6.1	---
	L2A = 9.6	C2A = 5.8	---
From insulator to taper: (13.7 to 11.2)	L1B = 34	C1B = 0.51	---
	L2B = 38	C2B = 0.46	---
First half taper: (11.2 to 10.2)	L1C = 31	C1C = 0.36	---
Second half taper: (10.2 to 9.2)	L2C = 15	C2C = 0.74	---
Photocathode: (9.2 to 0)	L1D = 22.2(d)	C1D = 0.730/d	R1D = 0.0177(R_s)
	L2D = 25.0(d)	C2D = 0.417/d	R2D = 0.0199(R_s)
	L3D = 28.6(d)	C3D = 0.362/d	R3D = 0.0226(R_s)
	L4D = 33.4(d)	C4D = 0.306/d	R4D = 0.0266(R_s)
	L5D = 40.1(d)	C5D = 0.250/d	R5D = 0.0319(R_s)
	L6D = 50.3(d)	C6D = 0.195/d	R6D = 0.0400(R_s)
	L7D = 67.3(d)	C7D = 0.139/d	R7D = 0.0536(R_s)
	L8D = 102.0(d)	C8D = 0.0845/d	R8D = 0.0813(R_s)
	L9D = 220.0(d)	C9D = 0.0278/d	R9D = 0.1749(R_s)

(In this table, d, the spacing between photocathode and the MCP input face is in mm, and R_s, the sheet resistance of the photocathode plus the sheet resistance of the MCP input face, is in ohms/square.)

The mean impedance level of the tube between any two radii for a low resistive loss is given by

$$Z_{ab} = \sqrt{\frac{L}{C}} = \frac{d}{\pi}\sqrt{\frac{\mu}{2\epsilon}}\,\frac{\ln(b/a)}{\left(b^2 - a^2\right)} \qquad (4)$$

Using this relationship, the data in Fig. 6 were derived showing impedance as a function of position. Some investigators have tried to define a fixed "tube impedance" that the pulser and connecting cable should match. The tube is a distributed system with a spatially varying impedance, and a "match" is of secondary importance. A prime consideration is to choose a low enough source impedance to drive the tube so that the risetime and amplitude of the pulse are not degraded too much before the pulse reaches the photocathode area.

Figure 7 shows our modeling of the pulser and tube connections. In NET-2 each transmission line is represented by a network made up of 20 LC sections. The capacitor next to the switch is chosen to increase the risetime on the pulse appropriately for the switch element being modeled. The 250-ps charged line will generate a 500-ps-long pulse when the switch is closed, and we have been using this in our system performance modeling studies. The series inductance represents the stray inductance in connecting to the tube.

Modeling results

NET-2 outputs graphs and tables of the voltage waveforms as a function of time for any node requested in the network. The data are quite voluminous, and to date, we have not reduced them to a convenient form for presentation. Basically, for a given set of entry conditions one looks at three factors: 1) the time for the pulse to propagate to the tube center, 2) the pulse amplitude at each photocathode node, and 3) the pulse shape and, in particular, the pulse width at each photocathode node. Based on these evaluations, we have set the parameters below for a subnanosecond camera system with a probable gating time limitation of 500 ps.

Pulser Z < 10 ohms
Pulser risetime < 300 ps
Terminating resistance equal to pulser Z_0
Connection series inductance < 2 nanohenries
Photocathode-MCP spacing = 0.25 mm (standard on present tubes)
Photocathode plus MCP sheet resistance < 20 ohms/square

Achieving these parameters requires modifying both tubes and gate pulse generator techniques as described below.

Tube modifications

We are procuring tubes with four modifications.

Photocathode sheet resistance

S20 and S25 multialkali photocathodes have inherently high sheet resistivity. When tubes are built for gating applications by ITT, the photocathode is deposited on a proprietary multimetallic substrate. This permits most 18-mm tubes to be gated for ~2.5 ns. For faster applications, GaAs photocathode tubes, which have very low sheet resistance (possibly <1 ohm/square) as well as higher quantum efficiency, might be used. Unfortunately, GaAs is even more prone to poisoning than multialkali cathodes, and for protection, generation III tubes use an Al_2O_3 film at the MCP input to protect the cathode from positive ion feedback or other contamination. This film requires significant electron energy for penetration, and thus the gating voltage requirement is ~900 V. Because of this, coupled with the scarcity of generation III tubes, we have given little serious attention to using GaAs, although we did some experiments with a standard military night vision tube during 1981. We were unable to produce the hollow center effect with this tube. To lower the sheet resistance of multialkali cathodes, various schemes have been used including implanted metal meshes, metal film underlays, and transparent metal oxide semiconductor underlays. Generally, the cathode is incompatible with many of the desired underlays. Thomas[40] reported a very promising system where a metal oxide semiconductor underlay is overcoated with a thin (2.2 μm) layer of silica to provide chemical isolation between the photocathode and the conductive substrate. In the fast gating mode, the pulse is coupled to the photocathode capacitively through the silica. At the frequencies involved, the capacitive reactance is low enough to be considered a direct connection. At low frequencies, a dc path is provided by direct connections to the edge of the photocathode. The knowledge of transparent semiconductor conductive coatings has increased markedly in recent years[41-43], and a coating with 85% transmission in the visible spectrum and a sheet resistance of <10 ohms/square can be made.

MCP input face sheet resistance

The input face of an MCP is commonly coated with Inconel, FeCr, or NiCr, none of which have particularly low resistivities. MCPs with gold coating thickness of ~0.4 μm are available and have sufficiently low surface resistivity.

Input connection inductance

To achieve a series inductance of <2 nanohenries, four flat tabs spaced 90° apart will be connected to both the photocathode and the MCP input. The tabs will have [illegible] very thin potting. The four photocathode tabs will have the same angular position [illegible] tube body as the four MCP tabs so that each can be extended into parallel transmission lines. The tab width will be ~8 mm, and the connections will be made to the tabs by [illegible] methods, i.e., mechanical pressure or room temperature-cured conductive epoxy.

The inductance of the internal connections to the MCP input face must be minimized. In present tubes, this connection is made with small pressure fingers, which have significant inductance.

Finally, it should be noted that standard tubes potted in Silastic often have [illegible] wire leads between where the lead enters the potting and where it actually connects to the tube electrodes, as can be observed by radiography.

Edge capacitance

The high lumped edge capacitance does not preclude fast pulsing; however, it imposes constraints on the pulser and drive circuitry. Therefore, we are having tubes [illegible] with the lumped edge capacitance reduced 50% by using ceramic insulators [illegible] twice normal thickness. The taper near the outer edge is changed to maintain the normal (0.2[illegible]) photocathode-MCP face spacing.

Gating pulsers and connections

We have not finalized the pulser system. The requirement to drive the tube at four points and present a 10-ohm pulser source impedance (really a 5-ohm source to the tube because the line is shunted by a 10-ohm terminating resistor) requires driving four 40-ohm loads simultaneously. With the exception of photoconductive switches, all switching techniques have too much jitter to rely on four separate pulsers. Splitting a single pulser to several loads can be done capacitively, with transformers, resistively, with tapered transmission lines, or with microwave combiners. We are evaluating the last three methods. Note that resistive dividers have high power losses. A 1000-V pulse on a 50-ohm line resistively divides into four 200-V pulses into 40 ohms, an 80% power loss.

A further complication is that on a real camera one usually wants to operate the phosphor at ground potential to avoid current leakage through the fiber optic coupling plate, and this puts the photocathode at high voltage. Thus one either floats the pulser at high voltage or uses coupling capacitors to provide isolation. If coupling capacitors are required, they must be carefully selected to provide low series inductance; therefore, ceramic capacitors designed for use at microwave frequencies should be used. Also, adequate dielectric strength must be provided because breakdown of a coupling capacitor would destroy the tube. Similarly, load resistors at the tube must have very low inductance, and microwave frequency resistors should be used.

Spark gap pulsers

Spark gaps can be made to generate pulses in excess of 1000 V with ~150-ps risetime, but it is very difficult to simultaneously produce very low trigger jitter. For a fast camera to be useful, the trigger jitter should be a small fraction of the exposure time. Laser-triggered spark gaps tend to have significantly lower jitter than electrically triggered gaps. Most spark gaps require frequent adjustments of gap, electrodes, and gas pressure, flow, and composition. We are not presently studying spark gaps. References 44 and 45 discuss high-performance spark gaps.

Avalanche transistors

We have used avalanche transistors for several years in various applications. A standard avalanche pulser is described in Ref. 34. Generally, high-voltage avalanche transistors have insufficient risetime for a <1-ns camera. There are low-voltage transistors (Motorola 2N4014, for example) with fast enough risetime but insufficient voltage swing or current capacity. Avalanche transistors can be connected in series for higher voltage either by a "Marx configuration" or by direct series connection. Generally, the risetime of an avalanche circuit does not degrade significantly with these higher voltage connections if current limits are not exceeded. Avalanche circuits can also be paralleled[46] to obtain higher current. With careful layout, many avalanche transistors could be connected to drive a fast tube, and trigger jitters of 50 ps are relatively easy to attain.

Krytron tubes with sharpening gaps

We have been able to produce <1-ns risetime pulses with Krytrons (EG&G KN-[illegible]) by careful connection geometry and adjustment of anode voltage. By [illegible] these tubes with a series sharpening spark gap and a shunt clipping spark gap, we have produced [illegible] pulses of 1300 V into 50 ohms. The trigger jitter is difficult to reduce [illegible] Krytrons are primarily useful for laboratory testing.

Step-recovery diodes

One of the most promising pulser techniques is to sharpen a slower risetime pulse with a step recovery diode (SRD). Risetimes of 100 to 200 ps at several hundred volts are potentially obtainable using diodes manufactured for high-power microwave frequency multiplication. Circuit design using SRDs is covered in Ref. 47. Another SRD circuit of paralleled shorting stubs can be used to clip the length of the pulse. Power metal oxide semiconductor (MOS) transistors might provide suitable drivers for SRD circuits. A [illegible] Soviet paper[48] describes a device functionally similar to a SRD [illegible] higher voltage.

Photoconductive elements (PCEs)

PCEs (Auston switches)[49,50] can easily switch >1 kV with <50-ps risetimes and with <2-ps jitter relative to the exciting light pulse. Where a suitable fast risetime and large amplitude exciting light pulse is available, PCEs are ideal devices. Several switches can be precisely synchronized relative to a common light source. We are [illegible] Los Alamos made PCE in our second tube test setup.

Tube evaluation

We have set up two tube evaluation systems based on generating a short [illegible] light pulse that can be accurately timed and adjusted temporally relative to the tube electrical

34[illegible]

gating pulse. In essence, one gates the tube and then illuminates the photocathode with the fast light pulse at some known time relative to the gating pulse. This allows us to observe the temporal light response of the gating process at various points across the photocathode surface.

Our first system (Fig. 8), which is fully operational, is based on a 1000-V, 1-ns risetime mercury relay pulser and a solid-state laser diode light source. The mercury relay pulser generates a fast rising 1000-V pulse, the major portion of which is sent through a low-loss delay line consisting of a 5-ns adjustable air line and a 75-ns cryogenic line operating in liquid nitrogen. The pulse length is then clipped to 600 ps and applied to the tube. A sample of the mercury relay pulse is used to trigger a Hamamatsu laser diode pulser, which has an internal trigger delay of ≃75 ns and an internal trigger jitter of ≃30 ps. The laser diode output is a 75-ps-wide, 850-pJ pulse at 820 mm (near infrared). The quantum efficiency of an S20 photocathode at this wavelength is near 0.01%, but it still has adequate sensitivity to allow testing the tube for temporal response. The silicon intensified target (SIT) TV system provides a convenient method of viewing the image intensifier tube response. The prime limitation of this test setup is the marginal risetime of the pulse from the Spire mercury relay pulser.

Our second test setup (Fig. 9) under development uses a nitrogen laser to both pump a dye laser emitting in the visible and to drive a photoconductive switch. The dye laser output is a ≤50-ps, 1-μJ pulse. The nitrogen laser (337 nm) provides about 50 μJ of energy split equally between the photoconductive switch and the dye laser. Accurate timing is provided by varying the light path length. This system will provide faster risetime and shorter pulse width on both the electrical and the optical pulses than the system in Fig. 9.

Conclusions

Lumped parameter circuit analysis can be used to evaluate performance of proximity-focused, microchannel-plate-intensifier based high-speed cameras including the tubes, [illegible] connections, and the gating pulse generator. The analyses indicate that these cameras can be gated in <1 ns and probably in 500 ps. This performance can be achieved using available electronic devices and tubes with the previously described modifications.

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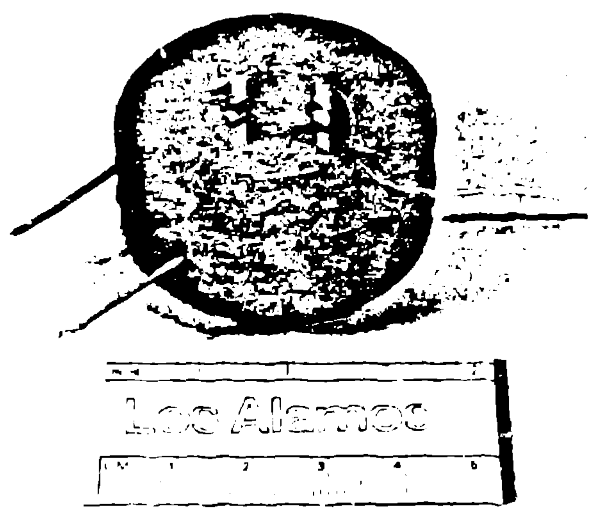

Figure 1. Potted 18-mm MCP image intensifier tube.

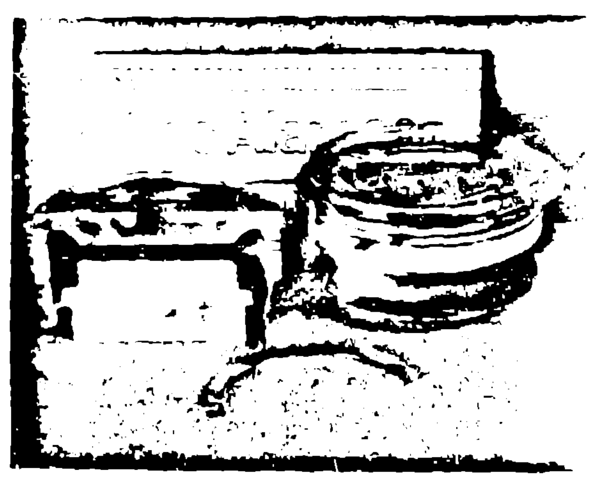

Figure 2. Unpotted 18-mm MCP image intensifier tubes. One of the tubes is cut in half to show internal construction.

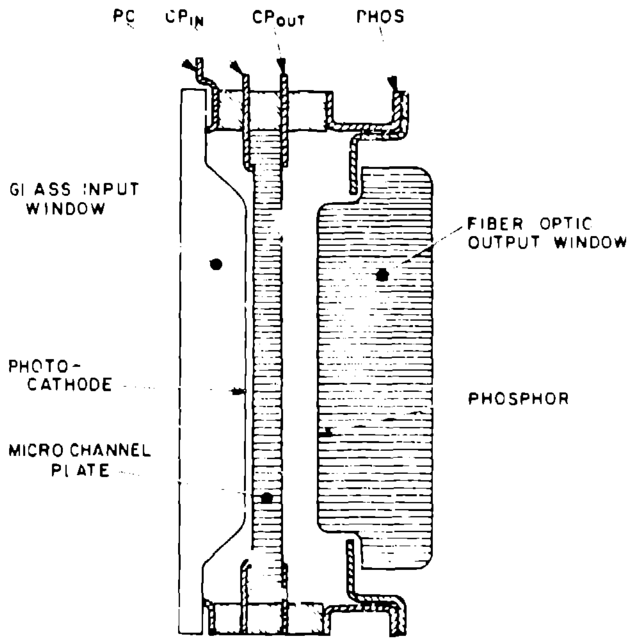

Figure 3. Cross-sectional drawing of a typical microchannel plate image intensifier tube.

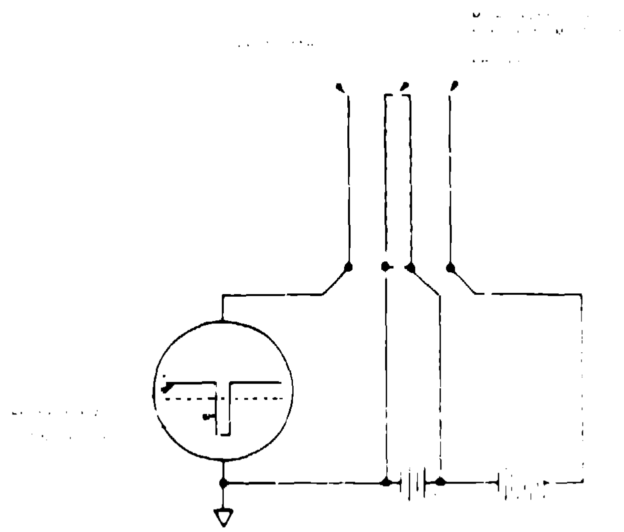

Figure 4. [illegible]

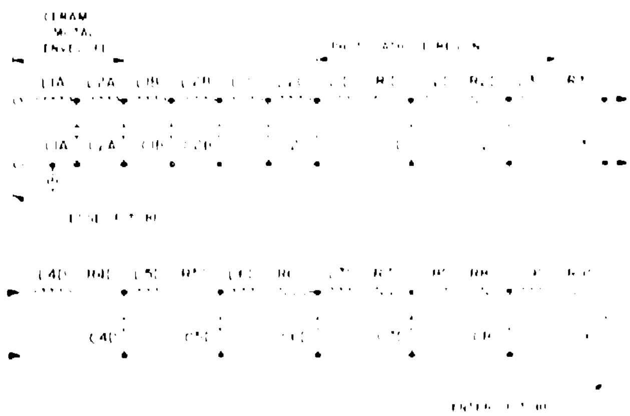

Figure 5. NET-2 model of an 18-mm microchannel plate image intensifier tube.

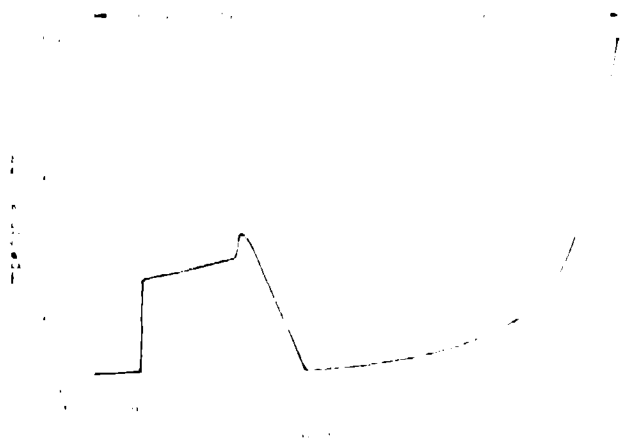

Figure 6. [illegible]

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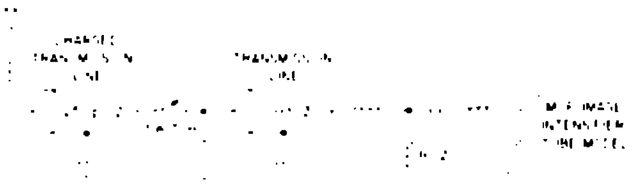

Figure 7. NET-2 gate pulse generator model.

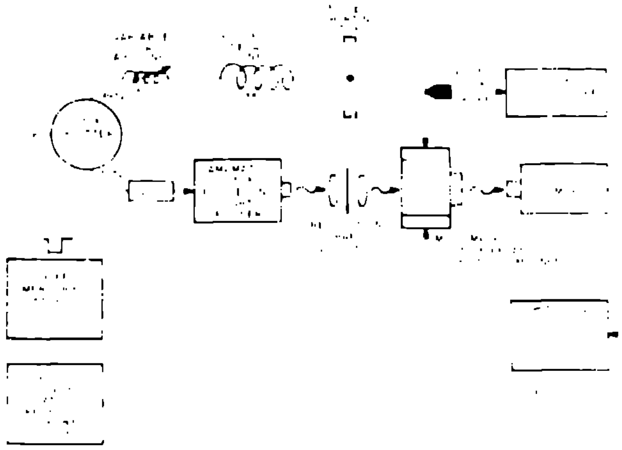

Figure 8. Mercury relay-laser diode system for tube gating characterization.

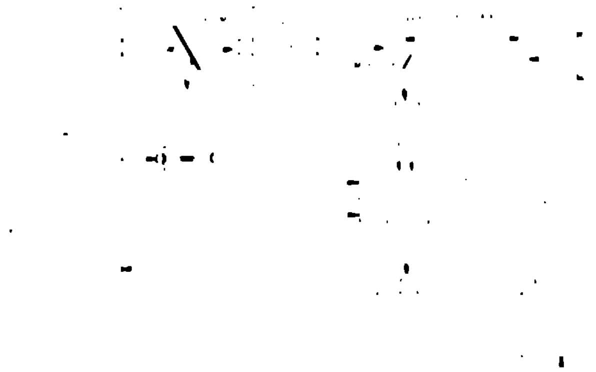

Figure 9. Pulsed nitrogen laser-driven [illegible] dye laser for tube gating characterization.