FAST-PULSE TECHNIQUES IN NUCLEAR COUNTING

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Proceedings
of the Second

SYMPOSIUM

on

ADVANCES IN FAST-PULSE TECHNIQUES FOR NUCLEAR COUNTING

Held at the
Ernest O. Lawrence Radiation Laboratory
Berkeley, California

February 12 and 13, 1959

LAWRENCE RADIATION LABORATORY
University of California
Berkeley

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The Second Symposium on Advances in Fast-Pulse Techniques for Nuclear Counting, sponsored by the Lawrence Radiation Laboratory, was held in Berkeley on February 12 and 13, 1959.

The first symposium had been organized by the Counting Panel of the Laboratory in February 1957 to assess the state of the art of detectors, transmission devices, coincidence circuits, amplifiers, scalers, and monitors and to better disseminate this information. Interest in fast-pulse techniques has greatly increased since the first symposium. The pressing needs of nuclear research have not only pushed the existing ideas to the limit but have also given rise to a number of new techniques.

The second symposium was organized to exchange and evaluate recent information, to explore the need for future study in the fractional-microsecond field of nuclear counting, and to consider photosensitive devices and pulse techniques. Generally the discussion was limited to the developments of the past two years.

The response to the second symposium was gratifying. The increase in representation of both United States and European laboratories was significant.

It is hoped that a useful exchange of ideas between the users and the manufacturers of counting and fast timing devices can be continued and expanded through the publication of these proceedings.

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The Second

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A-1. MULTIPLIER PHOTOTUBE TESTING

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I will describe some of the methods and results of multiplier phototube tests carried out by the Counting Research Group at the Lawrence Laboratory. Our group is concerned with investigation and evaluation of the various components of counting equipment, including phototubes. One of our aims has been to develop methods of testing directly and specifically those characteristics of phototubes that are of importance for counting purposes. I will include some results which indicate not only the present state of phototubes but also some desired improvements. In describing certain characteristics, I will necessarily include data taken on specific types of tubes, but this is not to be taken as faultfinding with those particular tubes. In fact, such characteristics usually differ from one type to another quantitatively rather than qualitatively. I am not attempting to criticize the manufacturers, but only to present certain problems that we have encountered.

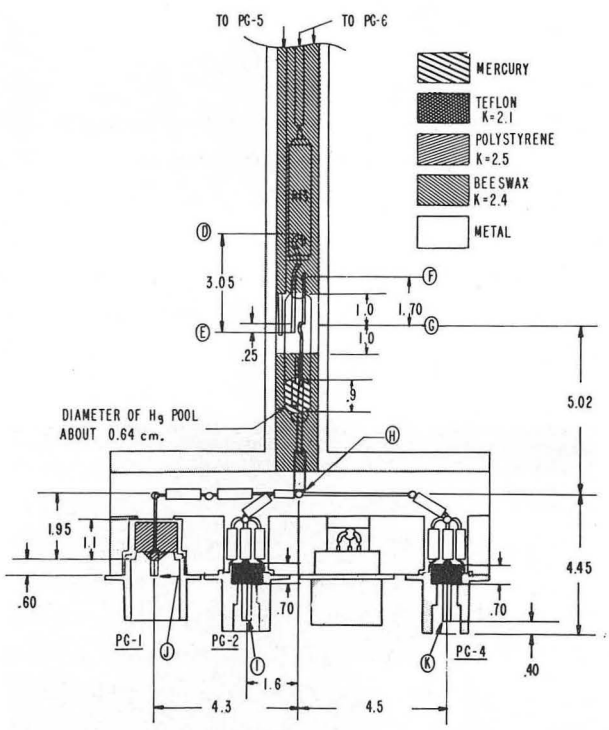


Fig. A1

First I will describe one of the most useful tools in phototube testing, the mercury-capsule light pulser. The construction of this device is shown in semischematic form (Fig. A1). The operation is quite similar to the familiar mercury-capsule electrical pulser except that the charging line is much shorter. The charging line consists of about 3 cm of line--the fixed contact of the mercury capsule plus a small portion of the lead in the 500-megohm charging resistor. This charging line is charged to potentials up to 5,000 volts. The contacts are closed magnetically, and a spark ensues. The spark is the light pulse. Simultaneously, an electrical pulse is generated which flows down the transmission line into the three output plugs, one at 125 ohms impedance, and two at 50 ohms impedance.

Figure A2 shows the external appearance of the pulser. The plate is normally mounted in a vertical plane for operation. Light emerges from the rear. The handle is used to control the position of a rotatable Polaroid film. There is also a fixed Polaroid film in the light path, and by crossing or uncrossing the Polaroid films one can vary the intensity of the light by a factor of about 100. One can also vary the intensity by about five or six orders of magnitude by changing the charging voltage.

Figure A3 shows a partially dismantled light pulser. One can see the mercury capsule embedded in the beeswax, and the magnetic driving mechanism on the right.

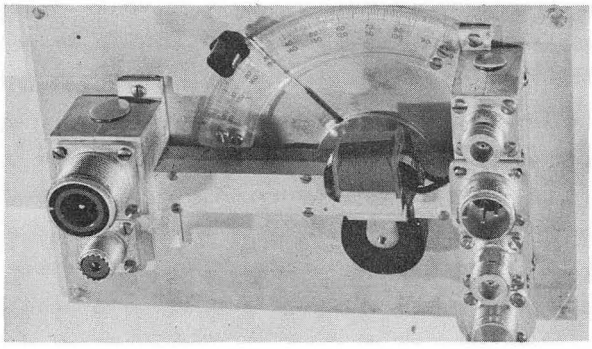


Fig. A2

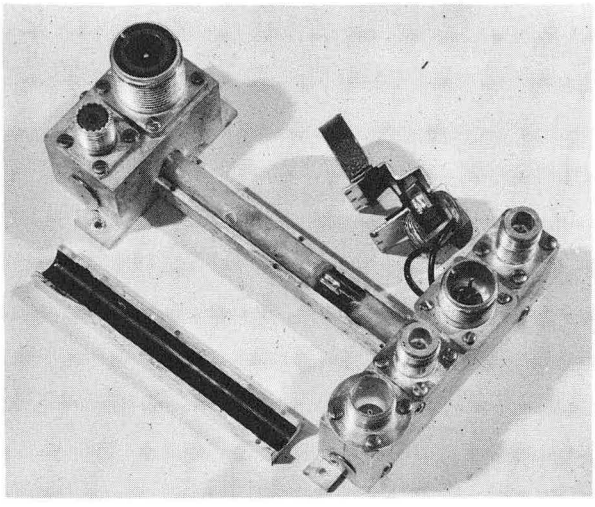


Fig. A3

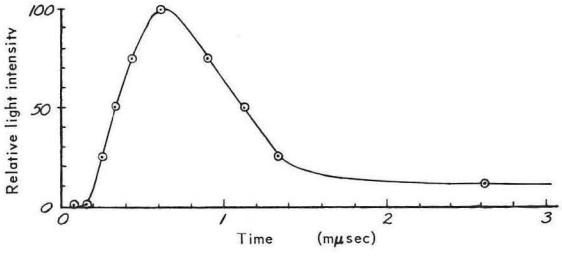


Fig. A4

The shape of the light pulse, of course, is of great interest. Fig. A4 shows the light-pulse shape as measured by a sampling phototube. The particular tube that we used was a 1P21 with an additional grid next to the photocathode; it was furnished to us by RCA. In making these measurements, we biased the grid negatively with a dc voltage, and then used the positive trigger pulse from the light pulser to gate the photocathode on for a small fraction of a millimicrosecond. By varying the relative timing of the arrival of the trigger pulse and the light pulse, one can sample the various parts of the light pulse and obtain the points shown. The light pulse rises to its peak amplitude and falls to about 25% amplitude in about 1 mμsec, and then some of the products in the gaseous discharge decay with a longer time constant.

The phototube that was used in making the measurements is shown in Fig. A5. The grid connection is made from the top; it is obvious that the geometry is not the best for introducing fast pulses into the tube. However, the tube was not constructed for such purposes. Even so, I believe it is worth mentioning this technique as a possible means of obtaining a good time resolution in coincidence or other timing applications.

The light pulser has many uses, among them measurements of transit times and transit-time differences in tubes. The useful feature is that the electrical pulse and the light pulse are generated simultaneously and come from the same process. One can accurately calculate the delays by measuring the cables with a ruler. Therefore, by presenting the trigger pulse and the phototube pulse on the same sweep of the cathode-ray tube, one can quite accurately measure the absolute time delay through the phototube. For instance, in Fig. A6 the top trace was made with a phototube voltage of 2,000 volts, the bottom with a phototube voltage of 2,700 volts. The difference in transit time is quite obvious. This middle trace shows a series of trigger pulses separated by successive delays of 5 mμsec.

An indication of the accuracy of time measurements that can easily be obtained with this light pulser is shown in Fig. A7, which shows some cathode transit-time difference measurements performed on an experimental tube made by Dr. Morton's group at RCA, Princeton. This tube has a fully curved cathode, curved on both the inside and outside surfaces. The cathode transit-time difference is the difference in tran-

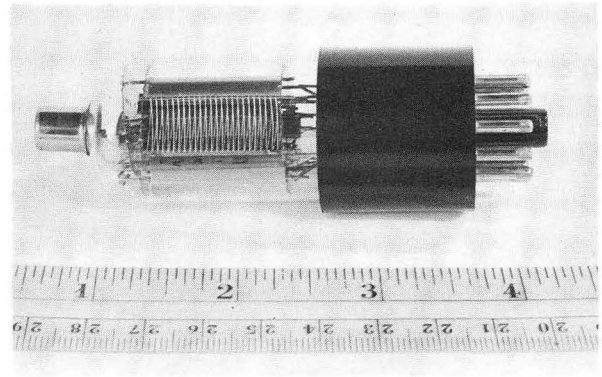


Fig. A5

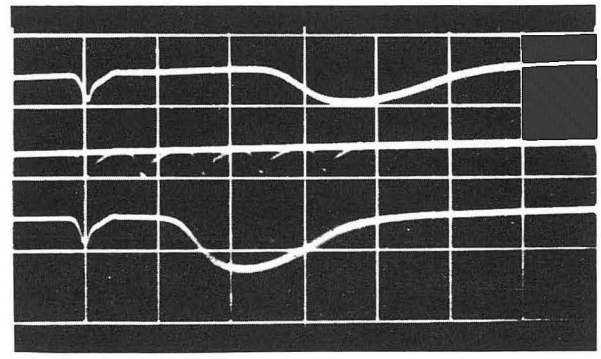


Fig. A6

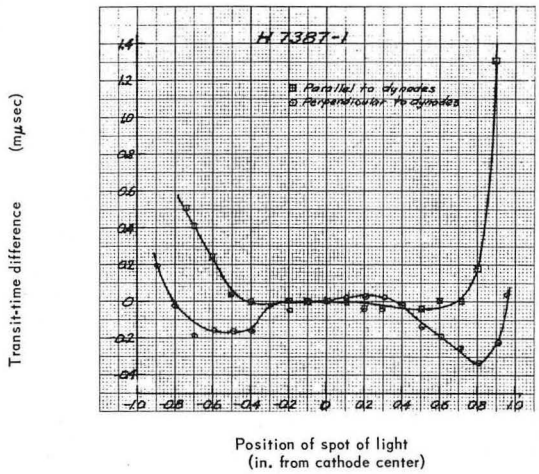


Fig. A7

sit time through the tube as a function of the portion of the cathode that is illuminated. On the vertical scale is the transit-time difference. The large divisions are 0.2 mμsec. The cathode position is plotted on the abscissa with the center of the cathode in the center of the scale. We usually take two such curves for a tube, one parallel to the dynodes, and one perpendicular to the dynodes.

It is a relatively routine matter to make transit-time measurements on a tube. The transit times as function of voltage are shown for some well-known tubes in Fig. A8. One finds that the transit time at a certain voltage varies from one tube to another (within a given tube type) by as much as 2 mμsec. Pulse-gain measurements are also very easily made with the light pulser and are quite useful. If the gain of a phototube is measured with a steady light source and dc meters, the effect of afterpulses is included in the gain measurement. This effect can be eliminated by measuring the gain with a pulsed light source such as this. By attenuating the light sufficiently, one can come to the point where there is on the average less than a single photoelectron per pulse. From probability formulas one can calculate that, if an output pulse is obtained from a phototube only 10% of the time that the light pulser is flashing, then of the pulses seen, 94% are originated by a single photoelectron, about 4% by two photoelectrons, and about 0.2% by three photoelectrons, and so on. Thus by assuming that all the pulses are due to single photoelectrons, one can make absolute pulse-gain measurements simply by measuring the charge in the output pulses. One can also compare the efficiency of collection from various regions of the cathode or from cathodes of different tubes.

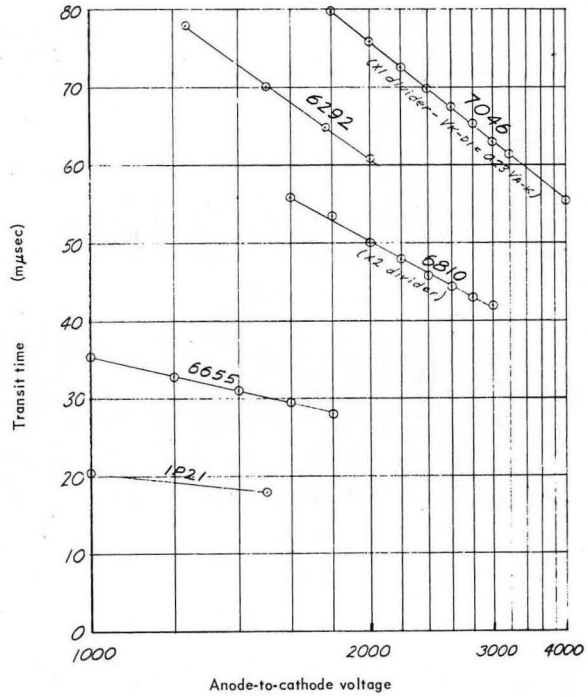


Fig. A8

Next I will talk about a group of tube characteristics having to do with noise, or--if you prefer--dark current. At the current gains of interest, dark current, although measurable with a dc meter, consists mainly of random pulses. One source of noise is thermionic emission from the photocathode. However, there are other sources of noise in most tubes which produce what one might call excess noise, which is over and above that due to the thermionic emission. One such source is light feedback. When space current flows in a typical dynode structure, light is generated at the same time. The intensity of this light has been measured, and is found to be roughly proportional to the current flowing in the multiplier.

Figure A9 shows the dynode structure of the 7046 with the base on the left and the photocathode out of the picture to the right. What happens when we turn off the room lights and turn on the phototube is seen in Fig. A10. This is the glow that occurs when current flows in the dynodes. This exposure was taken with about 1/2 ma flowing to the anode, and was a 1-minute exposure on a Polaroid film. I chose the 7046 for this picture because of its favorable envelope geometry; the envelope happens to be all glass in the region that we wish to photograph. All other phototubes that I have observed also exhibit this glow to some extent. This phenomenon (i.e. light

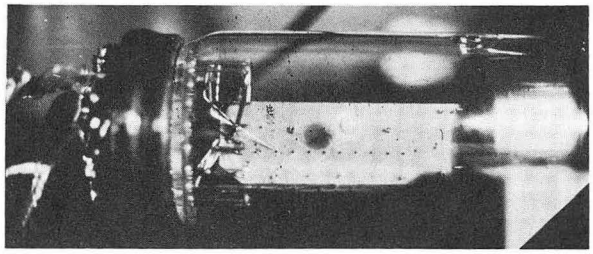


Fig. A9

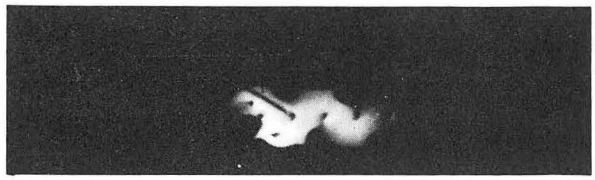


Fig. A10

emission from the dynodes) could be quite harmless provided the light did not return to the cathode. However, measurements of the light reaching the cathode of the 6810 type, taken as an example, indicate that the photocurrent that flows as a result of this light is about $1/(5 \times 10^8)$ times the anode current flowing at the same time. This means that when the dynode current gain reaches the value of 5×10^8, one has a positive feedback mechanism with a loop gain of one. You would expect it to regenerate, and it does. Thus we find that most 6810A's with glass dynode-support insulators regenerate when the gain reaches approximately 5×10^8. This is illustrated in Fig. A11, which shows the dc gain measured on a particular tube. The anode-to-cathode supply voltage is the abscissa; the ordinate is the anode current gain on a logarithmic scale. The three curves represent measurements of dc gain made with three different voltage distributions. The curve on the left (X1) is for a uniform interdynode voltage distribution. That on the right (X6) is a graduated distribution, with the voltage from Dynode 13 to Dynode 14 six times the voltage from Dynode 1 to Dynode 2. The center curve (X2) is for an intermediate distribution. As indicated by the boxed squares, the tube regenerates at very nearly the same value of current gain regardless of the voltage distribution used.

Another indication of the effect of light feedback can be seen from Fig. A12, which shows some "prompt" afterpulses from a phototube. The horizontal scale is 50 mμsec per division. On the lower trace, the first pulse is due to a light pulse. The two following pulses, successively weaker and separated by increments of about 50 mμsec, are afterpulses, the result of light feedback. The light travels from the anode region to the cathode in a fraction of a millimicrosecond, so that the time of a round trip is very nearly the transit time of the tube, i.e. about 50 mμsec. This tube was operating quite near the regeneration point.

The other trace shows the same phototube operating at a lower voltage and with approximately the same output current. One sees that at this voltage the effect of light feedback is quite negligible.

The foregoing remarks describe a light source whose intensity is a function of current. There are also sources whose intensity depends on voltage. These affect especially the lower-gain tubes, which require greater voltages to obtain a given gain. These sources probably arise because of high gradients within the tubes. For instance, one may get a small gaseous discharge between closely spaced points, or one may get field emission from a sharp point, causing electrons to strike the glass and produce fluores-

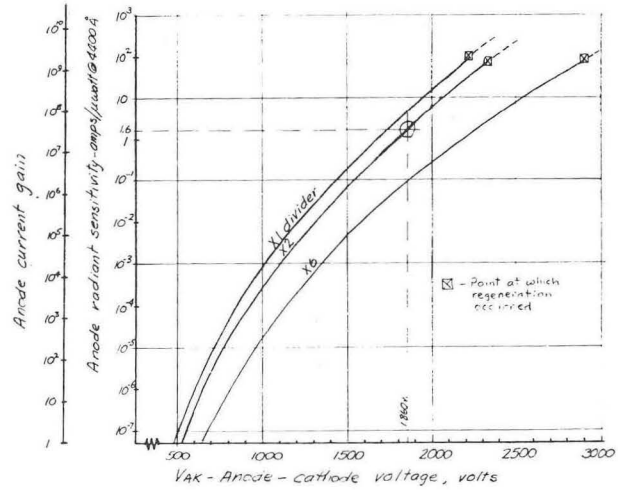


Fig. A11

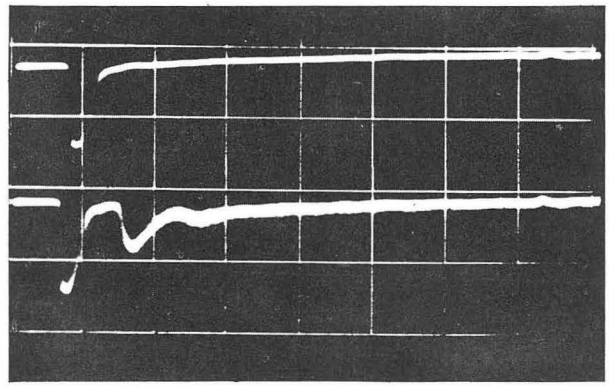


Fig. A12

cence. Sometimes small semiconducting particles may bridge the gap between points of different potentials. Many of these voltage glows can be eliminated, provided they can be located. They are often difficult to see since they are of low intensity.

Another source of excess noise is what we like to call the glowing filament. The symptoms of a tube that acquires a glowing filament--which has the effect of an incandescent light bulb built into the phototube--are sharply reduced gain and increased dark noise. A glowing filament is a small whisker of material that bridges across some electrodes in the tube. It has a low enough resistivity to short out the voltage-divider resistors associated with electrodes across which it bridges, and a high enough resistivity so that it glows or incandesces with the divider current shunted through it. These whiskers have resistivities typically about 100 times that of metals, and their resistance decreases with temperature, indicating that they are probably semiconducting. They actually appear rather frequently. We have taken data on 12 such whiskers in the past several years, and I imagine other cases have occurred here at the laboratory that have not come to our attention.

Figure A13 is a photograph of a DuMont linear-multiplier tube with a considerable amount of background lighting. However, the little white dot visible between Dynodes 1 and 3 is the light from such a glowing filament which is lodged between two of the early dynodes. Figure A14 is a view through the semitransparent cathode of a 6810 tube. The little jagged line between the cathode and focus electrode is not a miniature lightning bolt, but a whisker. It is in a very favorable position to light up the cathode and cause excess noise. These whiskers fortunately can be removed very easily simply by passing enough

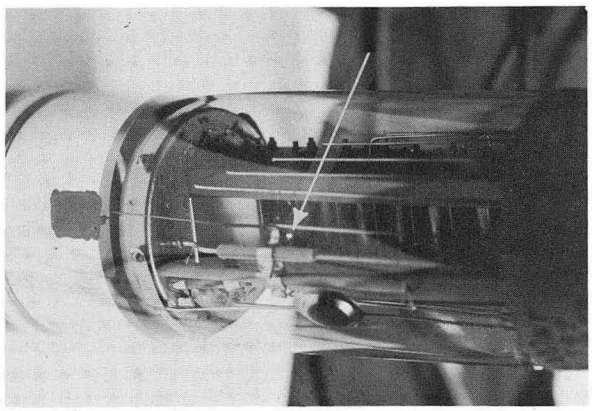


Fig. A13

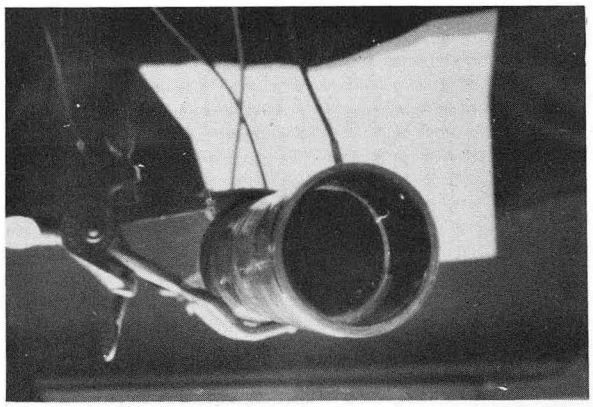


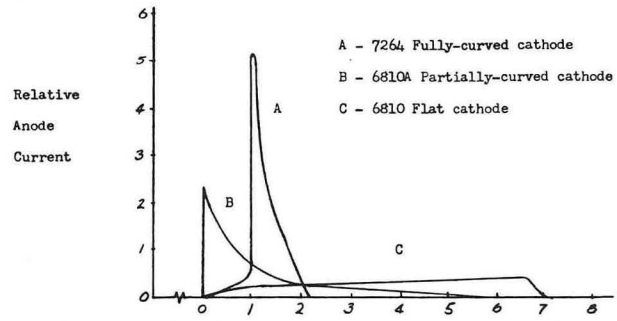
Fig. A14

current through them to vaporize them, after which the tubes apparently regain their former gain and noise characteristics.

It is interesting to speculate on what might occur if one could build a tube in which any desired voltage could be applied between pairs of dynodes. For instance, a 14-stage tube of silver-magnesium dynodes typically operating at 150 volts per stage now gives a gain of 10^9 with an average interdynode gain of 4-1/2. Published curves on the secondary-emission characteristics of silver-magnesium material indicate that its maximum yield would be 9 at a primary electron voltage of about 450 volts. Thus if one could place 450 volts between the stages and get an interdynode gain of 9, one could obtain a gain of 10^9 with only 10 stages. Since the transit-time spread varies as the square root of the number of stages, and inversely as the square root of the voltage between the dynodes, this 10-stage tube should have one-half the transit-time spread of the 14-stage tube.

The time-resolution qualities of phototubes are of great interest. To talk about time resolution, it is convenient to divide the tube into three parts: the multiplier, the cathode and focusing electrodes, and the output structure. I think the capabilities of the present multipliers are well known, and I'm sure we'll have further remarks in later papers about new developments in the multiplier field.

In the cathode region, great strides have been made in the last several years in reducing cathode transit-time spread. Figure A15 shows the time spreads of three well-known cathode shapes. Curve C is for flat cathodes such as in the 6292 or the older 6810 type. Curve B represents the partially curved cathodes such as in the 6810A or the K1549, and Curve A represents



Effects of transit-time spread of the multiplier are neglected
Curves are derived from CTTD measurements

Fig. A15

a fully curved surface such as in the 7264. In this graph we have derived from cathode transit-time difference curves the instantaneous anode current in fictitious multiplier phototubes having zero multiplier time spread following the time at which an impulse of light strikes the photocathode. We have neglected all but the cathode time spread. The horizontal scale is time measured from the instant the first electron strikes the anode. These curves all have the same area; therefore, as the time spread decreases, the instantaneous current rises. However, even with curve A, which illustrates one of the best cathode geometries commercially available to us, there still is a certain amount of time spread, and with small light pulses having only a few photoelectrons per pulse, one gets a time variation of up to 2 mμsec, depending on the portion of the cathode from which the photoelectrons are emitted.

Figure A16 shows two more examples of transit-time difference measurements made on RCA 7264's. They show extremes in characteristics that one finds in measuring various samples of tubes. The differences between the sets of curves may be due to differences in cathode radii of curvature. It is only fair to state that the tubes we have obtained recently are much more uniform in this respect than these curves might indicate.

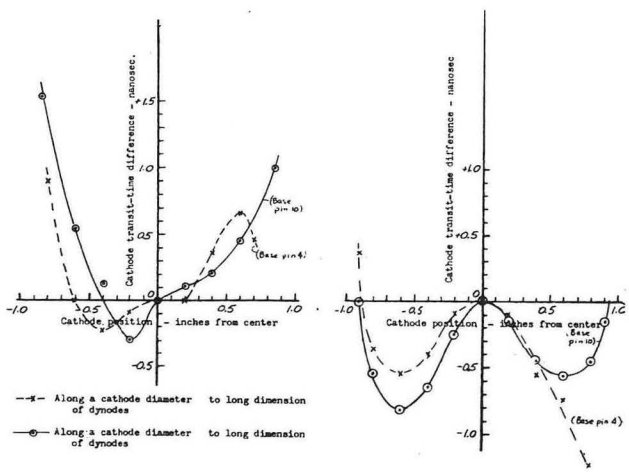


Fig. A16

The third part of the tube, the output structure, consists of the last dynode and anode electrodes and their leads. Their function is to convert the space-current pulse into an electromagnetic wave which is launched onto transmission lines. Since we are considering pulses it is convenient to think about the output structure in terms of transmission lines. Figure A17 shows the output structure of a 1P21 analyzed in such terms. For instance, the anode-dynode system has a Z_0 of 21 ohms over its 1.27-cm

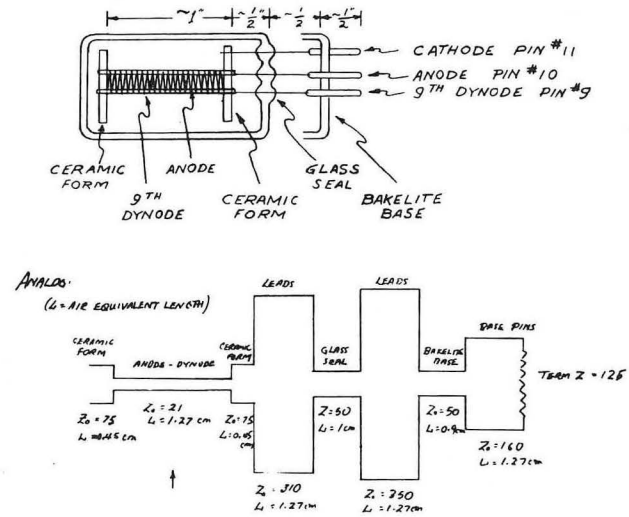


Fig. A17

length. The 6810 types can be approximately represented by a 40-ohm line equal in length to the anode and Dynode 14. The leads, base pins, and socket pins can be approximated by the appropriate length of 125-ohm line. If 125-ohm cable is then used between the base pins and the coincidence circuit or scaler, one has a continuous 125-ohm system except for the short length of 40-ohm line. Now if one applies a step function of current between the anode and Dynode 14, the output voltage rises in steps because of the successive reflections in the 40-ohm line. Drawing a smooth line through the curve, one can assign a rise-time number to it, which turns out to be (depending on which end of the 40-ohm line one introduces the pulse into) either 0.4 or 0.8 mμsec. Of course, the electrons in the actual tube alight on various parts of the anode—Dynode 14 structure, so that the actual rise time in op-

eration is somewhere between these two figures. Now obviously this is a rather small number compared with the time spread of this particular multiplier, and is apparently adequate for this tube. However, it indicates that a certain amount of care must be used in the design of output structures for faster tubes. The people who are doing this work are well aware of this problem.

Inasmuch as the lead from the anode terminal and the Dynode 14 structure going out through the base pins is approximately a 125-ohm structure, it seems a good idea to continue this same impedance, since we are using 125-ohm transmission lines external to the tube. The capacitor shown in Fig. A18 consists of two 4-kv ceramic capacitors molded in plastic with the spacing necessary to maintain a 125-ohm impedance. This is used to block the dc when the anodes are operated at positive high potential.

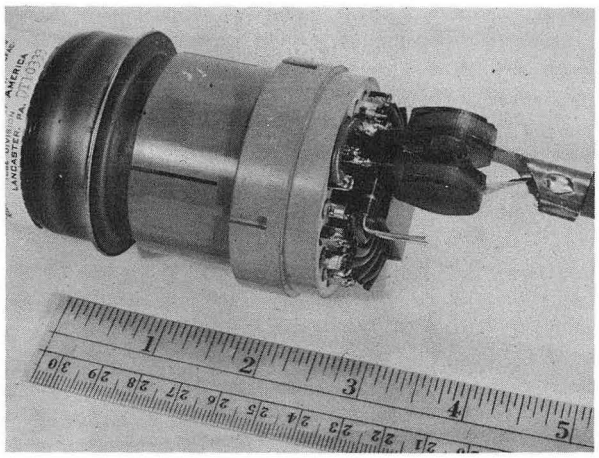


Fig. A18

The right-hand half of Fig. A19 shows what I call the mesa photocathode scanner. Imagine that you are looking obliquely down on a mesa rising above a plain and, further, that this mesa represents a circular photocathode surface and that the height of the mesa above the surrounding plain represents the sensitivity of the corresponding portion of the photocathode. You then can visualize the distribution of sensitivity over the photocathode by looking at this and getting the three-dimensional effect. The small wiggles on the traces are due to the phosphor grains on the flying-spot scanner that was being used. If one selects a section through the center of this mesa and varies the focusing-electrode voltages, one finds the patterns shown on the left in Fig. A19. One can accentuate the sensitivity of the outer portions of the cathode, or the center portions, but apparently in general it is not possible to optimize the sensitivity over the whole cathode.

One last remark, regarding magnetization of tube parts: some experimenters have found to their sorrow that when unshielded tubes are carried through high ambient magnetic fields the tubes may become permanently magnetized. This may reduce the gain by factors of from 10 to 100; magnetic shielding later put around the tube helps only to worsen the situation. These tubes can be degaussed; however, the loss of the experimenter's time is troublesome. It would therefore seem desirable to keep the number of ferromagnetic parts in the tubes to a minimum.

In conclusion, I would like to give due credit to the past and present members of our group who have contributed to the work described here. Quentin Kerns has been the group leader during this period. Other contributors are Norman Winningstad, Norman Seaton, Jacques Mey, Jerry Cox, and Bob Reynolds.

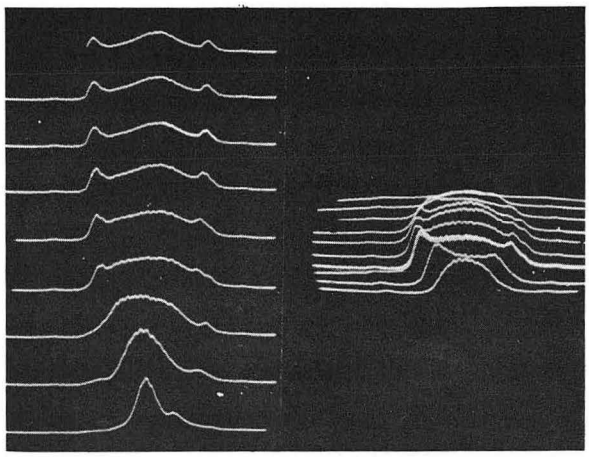


Fig. A19

Discussion

Morton (asked about the importance of maintaining 125-ohm output impedances in future phototube designs.)

Kirsten: The decision to use 125-ohm transmission line to transmit phototube pulses was based, in part, on available phototubes. For instance, the output structure rise times ($2.2\ Z_0C$, where Z_0 is the impedance of the transmission line load, and C is the output capacity of the phototube) of the 1P21's, 6810's, and other fast tubes becomes comparable to the multiplier rise times when Z_0 is made 125 ohms. However, it may be difficult to achieve a higher-speed output structure at a level of 125 ohms. In that case, I would say that if impedance level stands in the way of higher speed it should not be considered a serious restriction on future designs.

A-2. THE APPLICATION OF TRANSMISSION SECONDARY-ELECTRON EMISSION IN SCINTILLATION TRACK IMAGE COUNTERS AND FAST-RISE-TIME PHOTOMULTIPLIERS

Arthur E. Anderson
Westinghouse Research Laboratories, Pittsburgh, Pennsylvania

Introduction

The phenomenon of transmission secondary-electron emission in thin films offers important advantages over present techniques in amplifying weak photoelectric currents generated by light emission from scintillators used in high-speed pulse counting[1] and scintillation track imaging. Figure A20 is a schematic of the transmission secondary-emission direct-view image intensifier.[2] In this tube, electron multiplication takes place in a number of plane parallel vacuum-

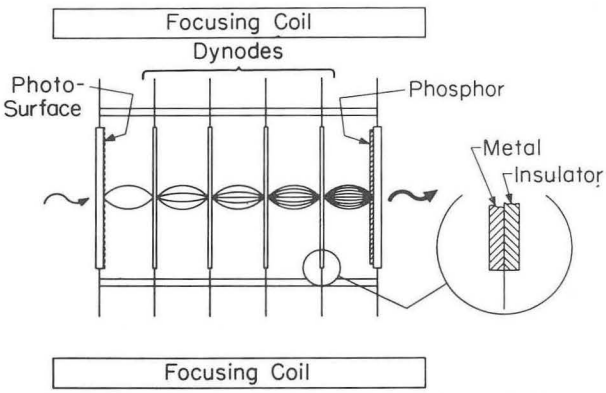


Fig. A20. Schematic of transmission secondary-emission intensifier.

spaced thin-film dynodes. These dynodes consist of thin films of a conductor in intimate contact with an insulator which has a high secondary-emission yield. The photoelectrons are accelerated to the first dynode, where they penetrate the conductor and insulator. Many of the secondary electrons produced in the insulator escape from the insulator and are accelerated by the applied electric field to the following dynode, in which the secondary-emission process is repeated. An axial magnetic field is used to focus the electron image on each dynode and finally on an output phosphor where the input image appears greatly increased in brightness.

A fast-rise-time photomultiplier is realized by using a similar plane parallel arrangement of thin-film dynodes and a coaxial collector in place of the phosphor shown. In this case the nearly uniform length of all electron trajectories and the high velocities to which electrons are accelerated between dynodes act to reduce the time spread of pulses during multiplication well below that obtainable in conventional front-surface multipliers.

Figure A21 shows a sealed-off transmission secondary-emission image intensifier. This tube is designed to operate in an 840-gauss focusing field. It uses a cesium-antimony photosurface and a zinc—cadmium sulfide output phosphor. First tubes of this type had electron gains of 500 and resolved six line pairs per millimeter.

Several experimental high-speed photomultipliers have also been built. Sternglass and Wachtel[1] have reported earlier on the multiplier

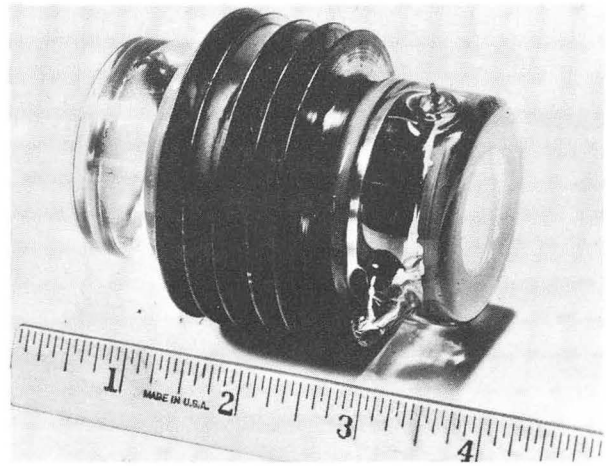


Fig. A21. A five-dynode transmission secondary-emission image-intensifier tube.

[1] E. J. Sternglass and M. M. Wachtel, Transmission Secondary-Electron Multiplication for High-Speed Pulse Counting, IRE Transactions of the Professional Group on Nuclear Science, Vol. NS-3, No. 4, Nov. 1956.

[2] M. M. Wachtel, D. D. Doughty, and A. E. Anderson, The Transmission Secondary Emission Image Intensifier, in *Proceedings of the Symposium on Photoelectronic Image Devices* (Academic Press, London, 1959); also *Proceedings of the Symposium on Image Tubes*, Engineer Research and Development Laboratories, Fort Belvoir, Va., 1958.

pulse rise time and transit time in a demountable seven-dynode tube. This tube had dynode gaps of 0.2 in. and an anode gap of 0.26 in.

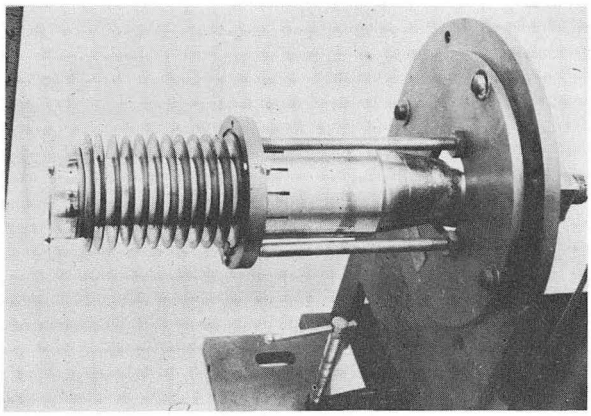


Fig. A22. A ten-dynode high-speed photomultiplier tube.

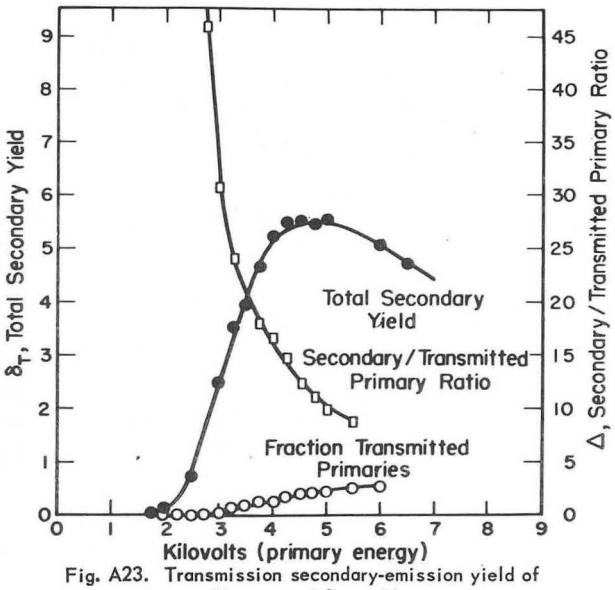


Fig. A23. Transmission secondary-emission yield of self-supported 2-cm film.

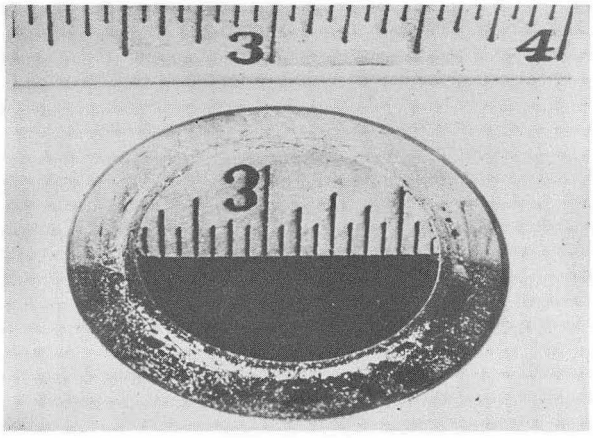


Fig. A24. A self-supported thin-film dynode.

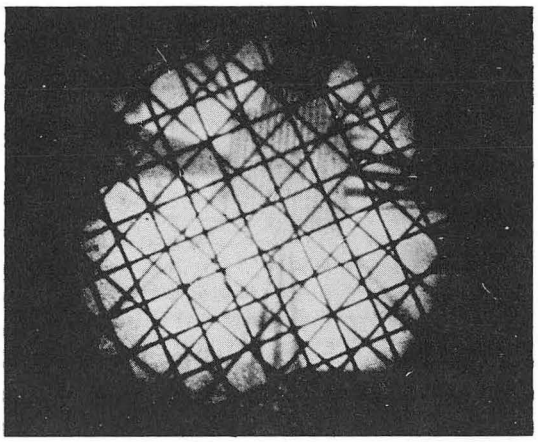


Fig. A25. Image transmitted by sealed-off two-stage tube.

Dynode-to-dynode voltage was 3.3 kv and the dynode-to-anode voltage was 600 v. They were able to place an upper limit of 1 mμsec on the pulse rise time in this tube. The transit time was 3.0±1 mμsec. More recently a 10-dynode photomultiplier having a gain of one million was assembled. This tube, shown in Fig. A22, operated successfully with 40 kv applied, but had insufficient gain to permit determination of the rise time of a pulse initiated by one electron leaving the photocathode.

Thin-Film Dynodes

Figure A23 shows the secondary-emission yield characteristics of a typical aluminum and potassium chloride thin-film dynode as a function of primary electron energy. Here secondaries are arbitrarily defined as all emitted electrons of energy < 50 ev. All emitted electrons of energies ⩾ 50 ev are considered transmitted primaries. Retarding-potential measurements show that about 50% of the electrons in the secondary group have energies < 2 ev and that less than 10% have energies > 10 ev.

The specular nature of these thin-film dynodes is shown in Fig. A24.

These films have been used successfully in five-stage demountable laboratory tubes, but it has not been possible to use self-supported films of this type in sealed-off tubes that are baked at high temperature prior to photosurface formation. Similar films supported on 90%-open-area electromesh do withstand the required baking, and have recently been used in sealed-off tubes. A photograph of a TV resolution chart reproduced on the output phosphor of a two-stage sealed-off tube is shown in Fig. A25. The mesh

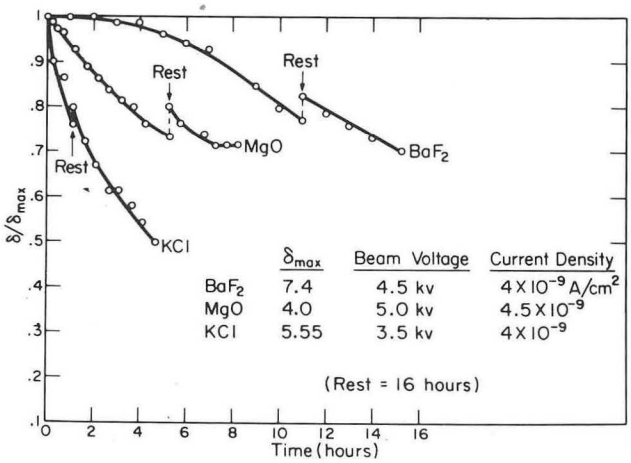


Fig. A26. Decay of δ with time.

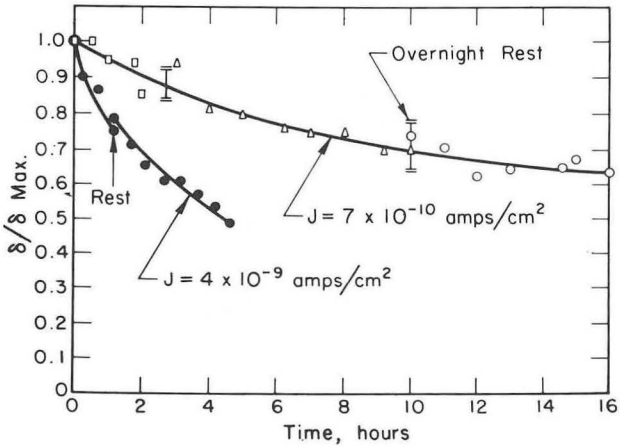


Fig. A27. Life test of Al-KCl dynodes.

supports of both dynodes are clearly visible. The support-wire spacing is 1.25 mm. The electron gain was 31, or 5.6 per stage.

Although the support mesh, even when registered from dynode to dynode, is objectionable in an imaging tube, it is of no concern in a high-speed photomultiplier. Stability of dynode gain is, however, of importance both in image intensifiers and in photomultipliers.

Dynode gain, δ, as a function of time for several thin-film secondary emitters is shown in Fig. A26. The life characteristics of recently developed magnesium oxide and barium fluoride systems are seen to be superior to the potassium chloride system previously described.

Decay of potassium chloride secondary emission with increasing primary current density and time was, as shown Fig. A27, largely responsible for limiting our effort in tube development to direct-view image intensifiers. Measurements indicate that image intensifiers using potassium chloride dynodes can pass 5×10^{-10} amp/cm^2 for about 100 hours before the gain of the final dynodes falls to one-half its initial value. Anode current densities of 10^{-9} to 10^{-10} amp/cm^2 at 15 kv are useful for image viewing and photographic recording.

The life of a high-speed photomultiplier using similar dynodes will be undesirably shorter. The larger average output-current densities in such tubes would seem to preclude the use of potassium chloride dynodes in these devices. A photocathode dark emission of 1000 electrons per cm^2/sec in a multiplier having a gain of 10^7 would limit tube life to about 10 hours. Improved thin-film dynodes of MgO or BaF_2 may, however, be capable of delivering the required photomultiplier-output current for sufficient time to be useful in special applications. Wherever continuously pumped demountable tubes can be used these dynodes may prove especially useful, since no activation procedure is required.

Besides providing improved life characteristics these newly developed thin-film dynodes show promise of eliminating the mesh support required with aluminum—potassium chloride dynodes. Several self-supported magnesium oxide thin-film dynodes, 1 in. in diameter, have been baked in vacuum to 400°C without rupturing. Figure A28 shows portions of two images transmitted by a magnesium oxide thin-film dynode. The fine mesh represents an image of 8 line pairs per mm.

Dark Current

In order to take full advantage of the high

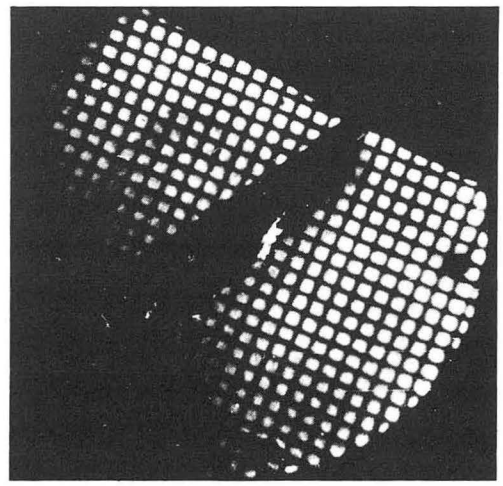


Fig. A28. Image transmitted by MgO dynode.

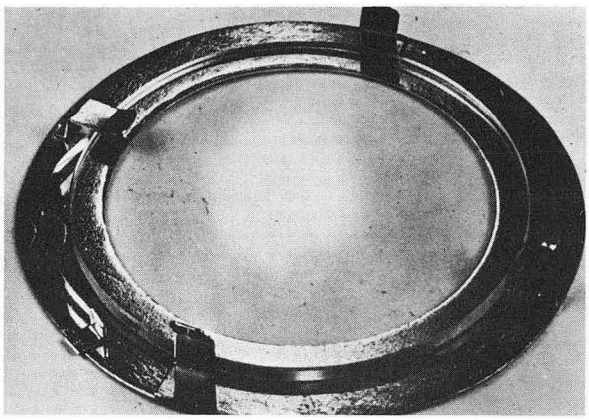


Fig. A29. Reversible cathode and mount.

gains possible in transmission secondary-emission devices it is essential that dark current be reduced to a minimum. The reversible-cathode technique developed by McGee of Imperial College, London, has been found very effective in reducing background.

The cathode assembly employed is shown in Fig. A29. This assembly is mounted at the desired distance from the first dynode and at sufficient distance below the input window of the tube to allow reversing the glass substrate in the tube. The photosurface evaporators are mounted above and to the side of the cathode assembly. The photosurface is formed on the upper face of the glass substrate during tube processing. After the completed tube is removed from the vacuum system the glass carrying the photosurface is released and remounted with the photosurface facing the first dynode. During tube operation the evaporating hardware remains in a field-free space and therefore it produces no spurious emission. By pumping on both sides of this assembly one can assure that very little cesium reaches the dynode sections of the tube. As a result recent image intensifiers have been almost completely dark with no input radiation and with full voltage applied.

Application to High-Speed Pulse Counting

The characteristics of the transmission secondary-emission multiplier that make it particularly desirable for high-speed counting purposes are:

a. Fast pulse-rise time due to nearly uniform electron path lengths through the tube and the high accelerating voltages used.

b. Uniformity of response over the cathode area.

c. Relative insensitivity to stray magnetic fields, particularly when the tube is oriented with its axis along the lines of flux.

d. Nearly 100% collection of electrons emitted by the cathode.

The only significant disadvantage is the high rate of deterioration of these dynodes under electron bombardment. The search for more stable materials is, however, continuing in an effort to overcome this difficulty.

Application to Scintillation Track Image Counting

Present tube-development effort is directed toward obtaining a direct-view image intensifier having a useful cathode diameter of 1 in., a photon gain of 10^4, and a resolution of 10 line pairs per mm. It is expected that tubes meeting these specifications will be produced in the near future. Upon completion of this task we are prepared to proceed immediately with the development of tubes specially designed to meet the requirements of short-time storage and gating associated with scintillation image counting. For this application we propose the use of two tubes in the arrangement shown in Fig. A30. A photon-to-photon gain of about 10,000 is required in each tube. The first tube will use a P15 output phosphor and the second tube will employ a P11 output phosphor. The second tube will be gated to receive information only from the desired event. The output of the last tube is best recorded on specially developed Super Ansco HyPan film using a second front-to-front lens arrangement. The proposed system has been analyzed in detail in a report by H. Kanter of our laboratory, which will be published shortly.[3]

[3] Westinghouse Research Laboratories Research Report 415FD314-R1, On the Secondary-Electron Image Intensifier in Nuclear Track Photography.

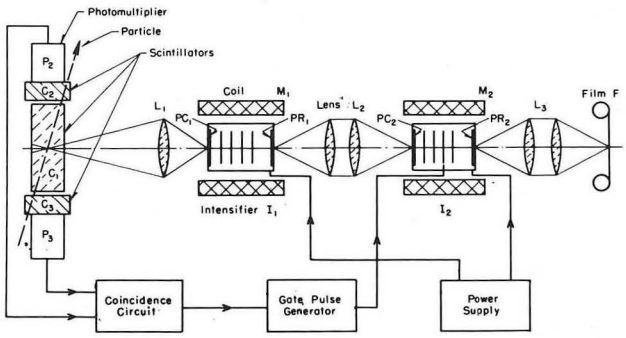


Fig. A30. Nuclear-track camera.

Acknowledgment

The author wishes to express his appreciation for contributions made to this paper by M. M. Wachtel, D. D. Doughty, Drs. H. Kanter, D. C. Lorents, and E. J. Sternglass. The continued interest and support of these investigations by the Engineer Research and Development Laboratories, Fort Belvoir, Virginia, the Department of Biology and Medicine of Atomic Energy Commission, and the Carnegie Institution of Washington, D. C., is also acknowledged.

Discussion

Question (on decay in secondary-emission ratio).

Anderson: I must point out that although we are using the same materials—the secondary emitters—used in front-surface multipliers, the technique of forming is quite different because they are thin films. We really don't know why they decay this way. The recovery indicates that there may be some centers formed that can be relaxed with time and temperature, but there is a real decay which apparently is irreversible. It may be due to difficulty in contact with the metal backing, but I can't say more than that.

Question (on the thickness of the secondary films).

Anderson: The potassium chloride--a vacuum-evaporated layer--is about 500 angstroms thick. For magnesium oxide, the actual measured thickness is on the order of 15 to 20 microns, but as I pointed out earlier, the density of the material is very low, so that the two systems (the potassium chloride and the magnesium oxide) are quite different in their manner of preparation.

The metal backing we've been using has been aluminum--about 300 to 500 angstroms thick.

Question: What is the spatial distribution of the emission?

Anderson: I assume your question is whether or not it is a cosine-type emitter. It peaks more in the forward direction than in the cosine. We are just now making measurements on this.

Question: What is the effect on the rise time of the transmitted electrons in these transmission photomultiplier tubes?

Anderson: I think it's definitely more serious in the imaging device than in the photomultiplier. I have some numbers here, calculated from the known energy distribution of the secondaries, indicating that the contribution to the rise time due to differences in initial velocity is about 7.7×10^{-12} sec per stage, so that I woudn't at this point be greatly concerned with the primaries, which go through. Certainly they give a spread. They cause a portion of the rise to be earlier, but only by a time that is short compared with any that I think are used today. It may later be of consequence. In imaging, the effect of the primaries is certainly more serious, and for this reason one hopes that the secondary yield per dynode can be increased over that available at present.

A-3. HIGH-SPEED PHOTOMULTIPLIERS AND ELECTRONIC DEVICES

George A. Morton
RCA Laboratories, Princeton, N. J.

A new multiplier being developed at RCA Laboratories under AEC sponsorship has time-resolution capabilities much better than those of conventional photomultipliers. Figure A31 shows an 11-stage multiplier of this type which has performance characteristics (as outlined below) in good agreement with design expectations. The early stages of the development of this tube were discussed at the Scintillation Counter Symposium nearly a year ago.

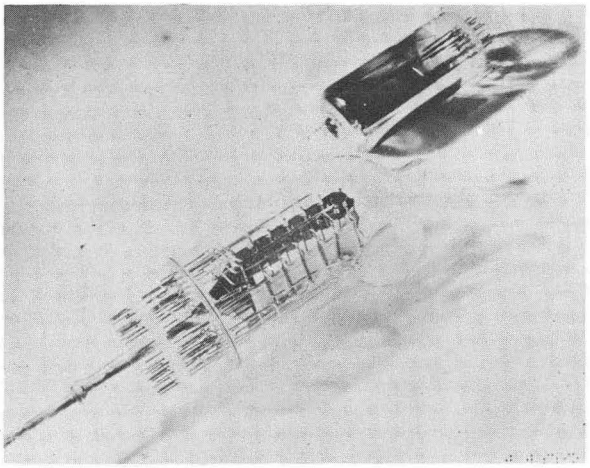


Fig. A31

The multiplier owes its good time characteristics to (a) a system of central electrodes operated at a high potential with respect to the dynodes, so that the velocities of the electrons over their entire trajectories are much higher than in conventional multipliers, and (b) the great care taken to make the trajectory lengths between conjugate points on pairs of dynodes as nearly equal as possible. Initially, it was hoped that this system of central electrodes could all be operated at one potential. Indeed, it was found possible--as described at the Scintillation Counter Symposium--to make fairly efficient six-stage structures with the central electrode system at one potential. However, if this same structure is used for a 12-stage multiplier, the additional six dynodes are so badly out of focus that they contribute almost no additional gain. It was therefore necessary to re-examine the structure and abandon the restriction that the central electrodes be all at one potential.

In the revised structure, the potentials of the electrodes making up the central electrode sysem increase in exactly the same way as the dynode potentials increase. Thus, the structure becomes truly iterative. To achieve this, it was necessary to redesign the dynode and central-electrode shapes. The accuracy of a rubber model is not sufficient for this redesign; therefore, a large-scale model was built in a vacuum-demountable system (Fig. A32). The dynode from which electrons originate was equipped with seven individually controllable thermionic cathodes, and the dynode on which the electrons impinge had an array of Faraday-cage collec-

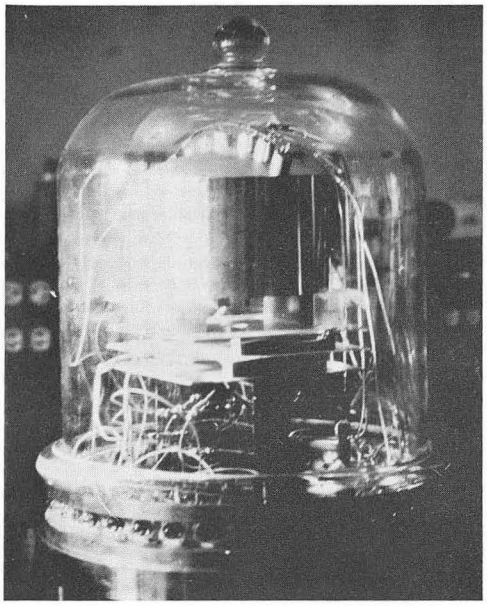


Fig. A32

tors. This permitted a point-by-point study of the electron trajectories. With the aid of this model, a satisfactory new design was evolved. The general configuration is shown in Fig. A33.

An 11-stage multiplier with an internal photocathode was built according to this design, and its electron optical performance was found to be very satisfactory. Measurements indicated that the loss of interdynode-space current to the

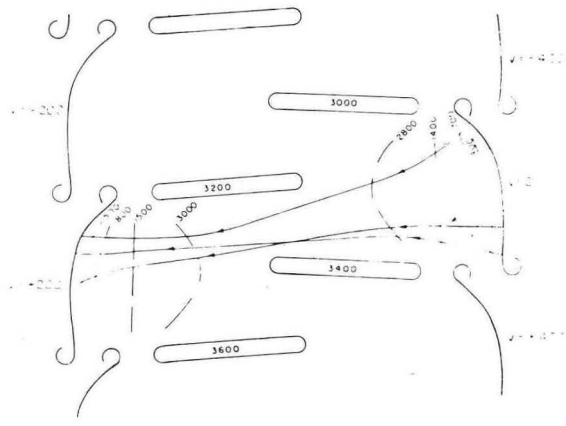


Fig. A33. One stage of central-electrode photomultiplier.

central electrodes, even in the high-current stages, was less than 10%; it is probably very much smaller in the earlier stages. A diagram of the structure is shown in Fig. A34. Figure A35 gives the focus spiral for this electron-optical arrangement. The focus curve was made from measurements on the enlarged model. Curve Max is the landing point of medium electrons. Curves L_1 and L_2 are the two extremes from any one starting point (i.e., from any given thermionic cathode). This focus curve agrees with the measured performance of the 11-stage tube with respect to current loss.

Figure A36 shows the measured gain as a function of interdynode voltage. Measurements were carried up to about 10^7, corresponding to 175 volts per stage. Pulse measurements were made to determine the saturated current output. Figure A37 shows the pulse-current amplitude obtained with 5-μsec light pulses as the interdynode voltage is increased. With voltages in the neighborhood of 175 volts per stage, an output current of 100 ma is obtained. Doubling the voltage on the last two stages almost doubles the maximum obtainable output current. It is

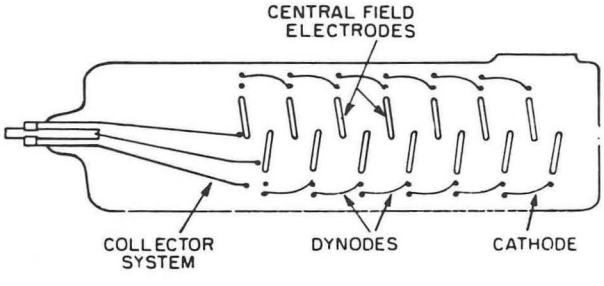
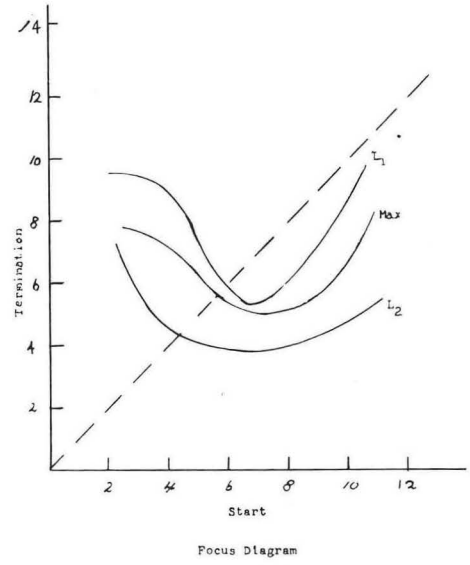


Fig. A34. Central-electrode photomultiplier.



Focus Diagram

Fig. A35

probable that, with further readjustment of voltages on the last few stages, a larger output can be obtained.

Attempts were made to measure the rise time of the output pulse obtained from a step function of light on the cathode. This was done

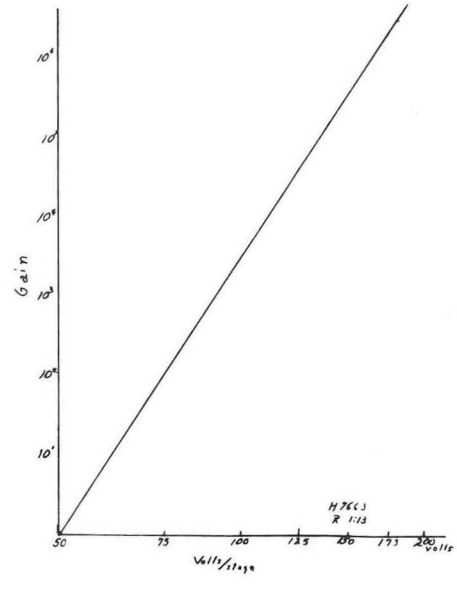


Fig. A36

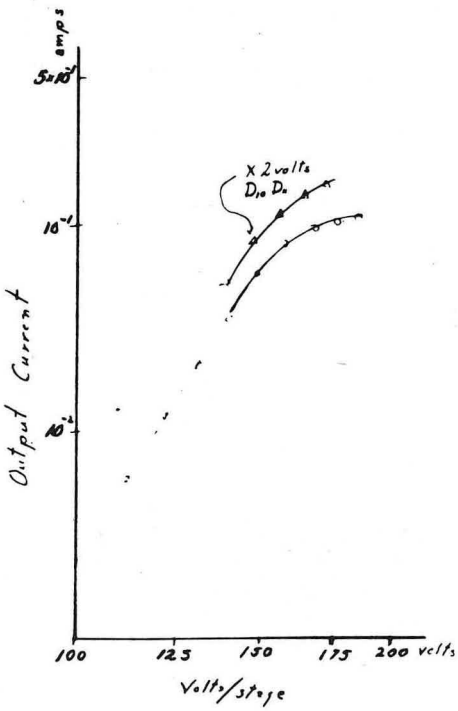


Fig. A37

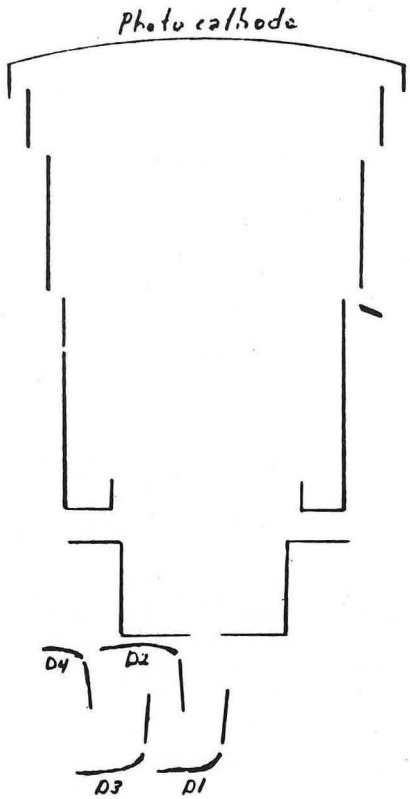


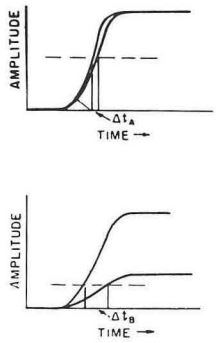
Fig. A38

with the aid of a spark source and an Edgerton oscilloscope. However, the combined limitations of the spark and the oscilloscope make this measurement quite questionable. In particular, the spark source, which was based on an earlier UCRL design, had a rise time of nearly 1 mμsec. If it is assumed that the electrical-pulse rise time of the spark source is similar to that of the light pulse, and if it is further assumed that the rise times combine as the square root of the sum of the squares, the rise time of the multiplier structure appears to be no greater than 5×10^{-10} sec. This means a time constant (or 1/e value) of about 0.2 mμsec.

A number of steps are still required to complete the tube. The electron-optical design of the structure itself is quite satisfactory. Mounting of the dynodes presents some difficulty. In the experimental tube described above, the structure was mounted on mica side strips. This is not entirely satisfactory from the standpoint of ohmic leakage. New structures now being built will have photoform glass supports which should give adequate insulation. Some additional shielding is required at the anode in order to reduce the displacement current induced by electrons in transit between the last dynode and collector. This can be accomplished rather simply. Finally, an on-the-window photocathode and electron lens system is being designed. The system to be used is shown diagrammatically in Fig. A38. It will be noted that the photocathode and associated electron optical system are at right angles to the main multiplier structure. This, of course, leads to an L-shaped tube. Such a shape has certain advantages and disadvantages. Among the disadvantages are that it does not lend itself to an "in-line" type of system, and, second, magnetic shielding of the tube is somewhat more difficult. An advantage is that it may be easier to keep the major part of the tube and electronics out of the high-energy particle beam.

Beam-Deflection Coincidence Tube

When one measures time intervals by the ordinary coincidence methods, the timing circuits are actuated by a specified voltage rise of the input pulses. Unless pulse-height discriminators are used to select pulses of one height only, an error can be introduced into the time measurements because of the finite rise times



$$\overline{\Delta t_A^2} = \frac{\beta^2}{N_e}\left(\frac{\sigma}{\sigma-1}\right)$$

$$\overline{\Delta t_B^2} = R^2/\left(\frac{dn}{dt}\right)^2 = \pi k \frac{\beta^2}{N_e}\left(\frac{\sigma}{\sigma-1}\right)$$

$$\Delta t = \sqrt{\overline{\Delta t_A^2} + \overline{\Delta t_B^2}} = \frac{\beta}{\sqrt{N_e}}\left(\frac{\sigma}{\sigma-1}\right)^{\frac{1}{2}}(\pi k+1)^{\frac{1}{2}}$$

WHERE: N_e = NUMBER OF PHOTOELECTRON
β = VARIANCE OF TIME SPREAD
σ = GAIN / STAGE
k = NUMBER OF STAGES

TIME DISPERSION EQUATIONS

Fig. A39

of the pulses, and the fluctuation in their amplitudes. This is clearly in evidence in the equations giving the time resolution obtainable with a scintillation counter shown in Fig. A39. To a first approximation, the time error may be thought of as consisting of two parts; one due to the true time jitter of the photomultiplier, the other due to the rate of rise of the output pulse and the statistical fluctuation in the amplitude. This second part is large and becomes increasingly important in high-gain multipliers, in which the number of stages is large, since the rise time of the output pulse increases with the square root of the number of stages. The second time error can be considerably reduced if the coincidence circuit is actuated by a definite fraction of the total rise of the output pulse rather than by a fixed voltage. A ratio coincidence circuit can be very easily devised with the aid of a beam-deflection coincidence tube.

A beam-deflection coincidence tube is shown in the diagram in Fig. A40. It consists of a gun producing a fine electron beam focused onto an

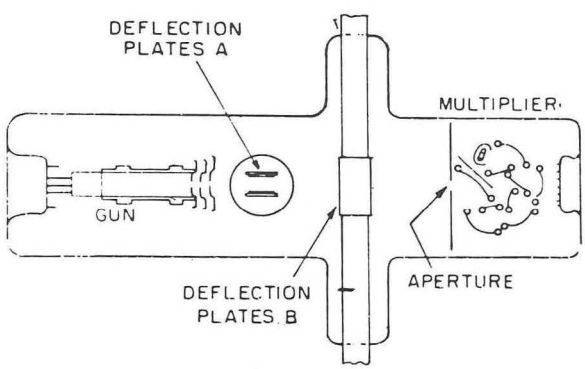


Fig. A40. Beam deflection coincidence tube.

apertured disk. Back of the aperture is a 10-stage circular multiplier. The beam is deflected by two pairs of deflecting plates mounted at right angles to one another. These plates are designed as parts of a 50-ohm transmission line which runs through the tube, so that they may be terminated in such a way as to avoid reflection (or can go on to other detecting equipment). A tube of this type is shown in Fig. A41. The tube has a sensitivity of 4 to 5 volts per millimeter with the beam operating at 1000 volts. The beam diameter and aperture are each less than 100 microns. The multiplier gain will run from a few thousand up to a million depending upon the operating conditions. With 0.1 μa in the beam current, ample signal is obtained from the multiplier.

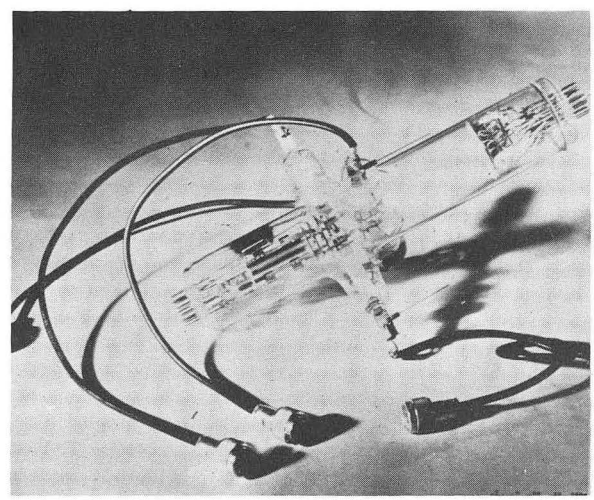


Fig. A41

One way of using this tube for ratio coincidence is as follows:

If A and B are the two scintillation-counter heads that give the signals indicating the initiation and termination of the event, the signals from A are applied to one set of deflecting plates and those from B to the second set. Two signals are taken from each scintillation-counter head. One comes from the last dynode through an appropriate attenuator onto the deflecting plates. The second is from the collector, and after a delay of a few millimicroseconds, is applied to the same pair of plates. The two pulses will be proportional to each other but opposite in amplitude. The operation of the coincidence system can best be explained with the aid of Fig. A42. It is as follows. In the absence of the signal, the two pairs of deflecting plates have applied to them a very small dc bias so that the beam strikes the apertured disk about one spot diameter below

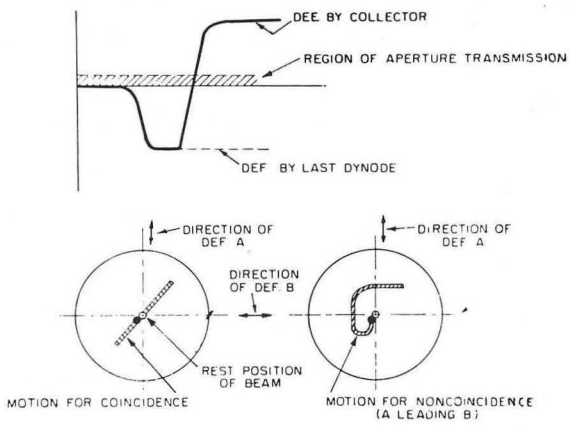


Fig. A42. Operation of beam coincidence system.

and to the left of the aperture. A signal from the last dynode, reaching the vertical deflecting plates, deflects the beam downward. Then, upon arrival of the pulse from the collector, the beam is deflected back up. Since the dynode deflection is a fixed fraction of the upward deflection, the beam crosses the region of the aperture at a time corresponding to that at which the pulse from the collector has risen a fixed fraction of its total height. A similar sequence of events occurs at the horizontal deflecting plates. When the two sets of pulses are in coincidence, the beam is first deflected downward and to the left along the diagonal line, and then retraces that line, crosses the aperture--giving rise to an output signal from the deflection-tube multiplier--and then continues diagonally upward and to the right. If the two sets of pulses are not in coincidence, the beam will follow a circuitous path on the aperture disk and will not cross the aperture, so that no coincidence signal is obtained.

Initial tests have been made on these beam-deflection tubes. Times in the region of 10^{-11} sec are easily obtained. In making coincidence measurements of the output from a Type 7264 tube with the electrical signals from the spark, the optical light path was varied. A full width at half maximum of the resulting time-distribution curve is about 0.25 mμsec.

Dr. R. W. Engstrom of the RCA Electron Tube Division, Lancaster, has given me some material on their latest developmental tubes which I would like to review briefly.

The RCA7264, shown in Fig. A43, has been in production only a short time. Some of the time characteristics of this tube were discussed in the first paper this morning. Figure A44 shows the arrangement of the electron optical system between the photocathode and first dynode for insuring uniformly high collection efficiency and good time characteristcs. This same figure shows a curve giving the time difference between an electron leaving the center of the cathode and one from a distance r from the center, measured on a laboratory prototype. The tubes that have been made at Lancaster have time characteristics indicating a need for some slight adjustment of the lens system but, nevertheless, their time accuracy is very good. The output-current characteristics of this tube when operated within the voltage ratings given in the technical bulletin depart from linearity by less than 10% for currents up to 0.7 amp.

The C7264 is a developmental tube which closely resembles the RCA7264 in its external

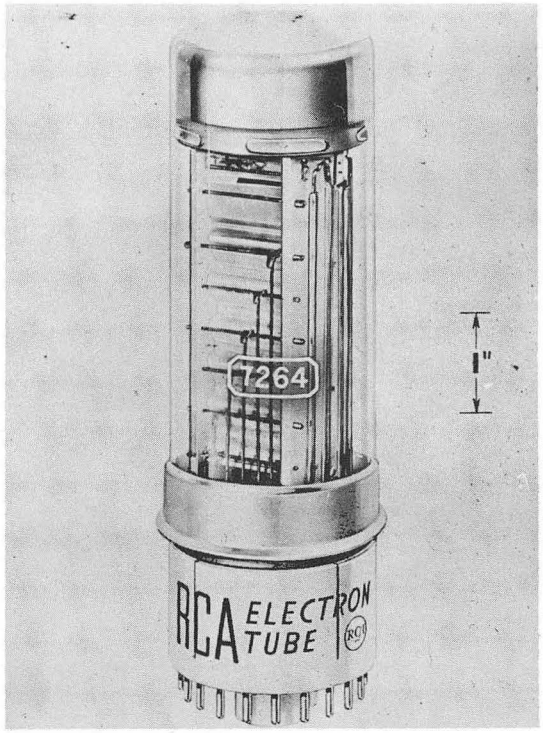


Fig. A43

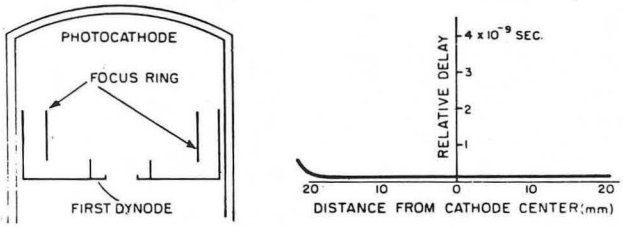


Fig. A44. Time-corrected photocathode lens system.

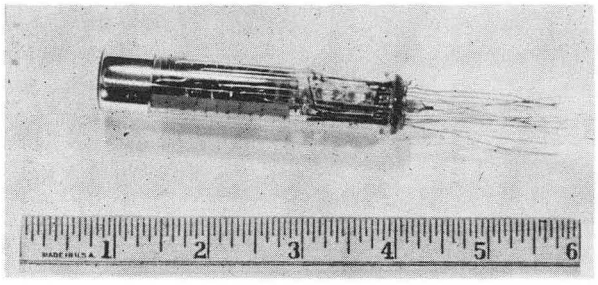


Fig. A45

appearance. This multiplier incorporates a new structure which should be slightly faster than previous tubes, and its collection efficiency is significantly better. The multiplier is of the linear type with newly designed dynodes. The better collection efficiency and time characteristics of this new multiplier are obtained by making the right-angle turn required to bring electrons from the photocathode into a linear structure extend over four dynodes, instead of confining the turn to the first dynode alone, as has been done in such structures as the 6810A and the 7264. When the turn is made with the first dynode only, the working area of this dynode is rather restricted and, furthermore, the time spread between electron trajectories originating at different points is large.

Figure A45 shows a nine-stage, 3/4-in.-diameter multiplier, the C7204. This tube may be of interest where space is at a premium yet good time characteristics are required.

Finally, I would like to mention the RCA7236, which is similar to the 6810A but employs a tri-alkali (S-20) cathode. This cathode has a considerably wider spectral response than does the S-11 cathode commonly used for scintillation counting. Furthermore, its thermionic emission is somewhat lower than that of an S-11 cathode and the cathode can be cooled to liquid air temperature without becoming so resistive as to be inoperative.

Leaving the subject of photomultipliers altogether, I would like briefly to discuss the intensifier orthicon, which I believe may have considerable importance for scintillation track imaging. At the 1957 Symposium on Millimicrosecond Pulse Techniques for Nuclear Counting, the possibility of using this type of pickup tube for track imaging was described. At the time, it was considered that a three-stage intensifier orthicon would probably be required in order to obtain sufficient sensitivity to see single electrons from the photocathode. Improvements in constructional and activation techniques in the past two years have made it possible now to obtain gains as high as 50 or more per stage, so that a two-stage structure will give the required gain. The construction of the two-stage intensifier orthicon is shown in Fig. A46. Electrons from the primary photocathode are electrostatically focused onto the first intensifier screen. This screen consists of an aluminized phosphor supported on a thin transparent membrane which is coated on the other side with photoemissive material. Electrons from the primary cathode falling on the phosphor of the intensifier screen cause the release of photoelectrons from its cathode. These electrons are in turn focused onto a second similar intensifier screen and the electrons from the second intensifier are focused onto the storage target of an orthicon pickup tube. As a result of the intensification, each primary photoelectron causes a charge of several thousand electrons to be stored on the target. This charge is sufficient to give a signal greater than the beam noise of the tube.

The intensifier orthicon has certain advantages over the direct-view image tube for scintillation track imaging. The video-signal output from the

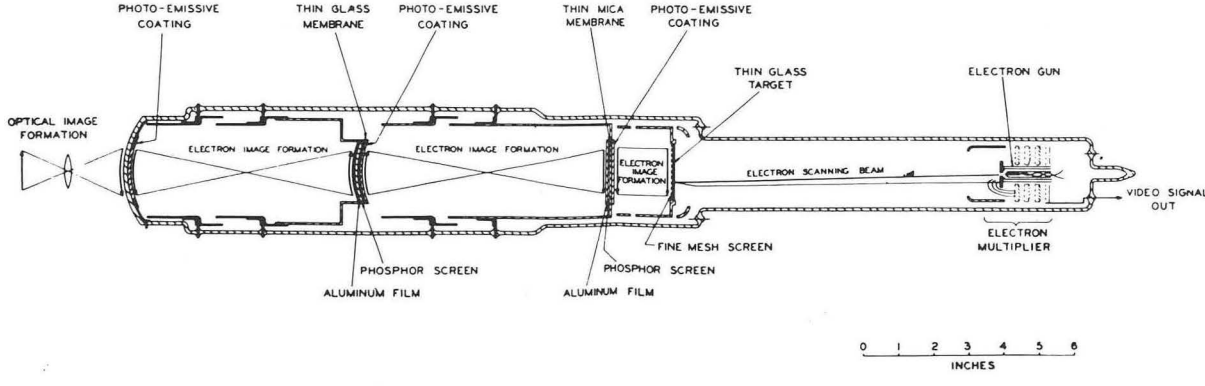


Fig. A46. Intensifier orthicon.

tube can be amplified any desired amount by a video amplifier whose characteristics can be adjusted to give optimum contrast and background level on the viewing tube. Furthermore, it is possible to store the video signal on a magnetic tape so that the signal can be processed later by a computer to avoid the necessity of having to study a large number of photographs individually. Figure A47 shows the measured performance of the intensifier orthicon, demonstrating that the tube performs as a photoelectron noise-limited pickup device having a quantum efficency of 10%.

The devices and results described in this paper are possible only through the work of a large number of people at RCA Laboratories. In particular, I would like to acknowledge the contributions of Dr. J. A. Baicker and R. M. Matheson in connection with the development of fast multipliers and the beam deflection tube, and of Dr. J. E. Ruedy for the intensifier orthicon. I would also like to express my thanks to Dr. R. W. Engstrom for the material on photomultipliers of the RCA Electron Tube Division of Lancaster. The work on the high-speed multiplier is being sponsored by the Atomic Energy Commission and that on the intensifier orthicon by the Air Force.

Discussion

Roberts: Are there any plans for production at Lancaster of this high-speed multiplier and the coincidence tube?

Morton: As soon as we finish in the laboratory I think Lancaster will be interested in doing this. There will have to be some sort of survey made to find out whether or not they can afford to do it without help. I haven't actually coaxed them on this coincidence tube, yet, but I think they will be interested in it. And I think it will be a fairly simple tube for them to make.

Question (asked for comment on the 50-ohm output impedance level).

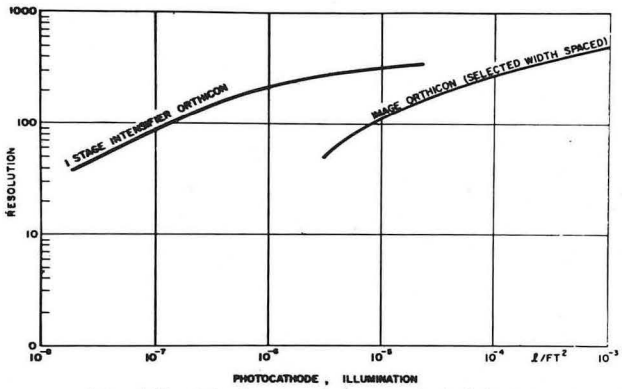


Fig. A47. Calculated performance of ideal device.

Morton: Well, it is our feeling that as more and more is asked of the time resolution the output impedance will have to be lowered. We hope that it doesn't have to go below 50 ohms, but 50 ohms is a quite convenient type of line to work with. That is why both the central-electrode multiplier and the coincidence tube are designed for 50 ohms.

Question: On the fast photomultiplier you described, what is the diameter of the photocathode?

Morton: The diameter that we are designing at present is 2 inches. We will start with the S11 cathode.

Question: How is the rise time of the light source measured?

Morton: We assumed that the light would follow the current, and what we measured was current.

Question (regarding the RCA 7264).

Morton: It is the tube that has the same structure as the 6810 but has a fully curved cathode and a redesigned input structure.

Question: Was the photomultiplier tube used under weak light conditions when the resolving time of the coincidence tube was measured?

Morton: In the results that I mentioned, it was not tested that way. We hope to do that.

A-4. DESIGN AND PERFORMANCE OF PHOTOTUBES INTENDED FOR NUCLEAR PHYSICS APPLICATIONS

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In view of nuclear research applications, in particular scintillation counting in high-energy physics, LEP (Laboratoires d'Electronique & de Physique Appliquées, Paris, France) has developed several specially designed photomultipliers. These tubes contribute to the accuracy of detection in two ways: by a small rise time of the anode current when excited by a light discontinuity; and by delivering this pulse at a high enough current level to attain a signal output of several volts across a low impedance, thus making unnecessary further electronic amplifiers.

There are two types of LEP photomultipliers for physical research. Laboratory type 204 (commercial type 56 AVP) has a useful cathode diameter of 1.60 in. while laboratory type 206 has a cathode diameter of 4.33 in. Both use the same multiplier section. As a result, performances that are determined by the dynode array are the same for both types. This is the case for current gain and maximum output current.

A curve relating output current to incident light flux is shown in Fig. A48. It is to be noted that nonlinearity is less than 5% at currents of at least 300 milliamperes. The potential distribution on the tube elements is also given in the figure.

Since normally only a few photons are available from each scintillation, attention must be paid to the photocathode quantum yield, the photoelectron-collection efficiency of the input electron optics, and the ability to operate with a large current gain. To achieve high gain, there are fourteen dynodes which are designed to work in the 100- to 150-volt range.

They can be operated, however, at up to 500 volts without damage if this is necessary for large output currents. Gains of 10^8 or higher are commonly used without instability caused by photonic or ionic regeneration. The equivalent cathode dark current is less than 10^{-15} amp/cm^2, and sometimes as low as 10^{-16} amp/cm^2.

The $SbCs_3$ type of photocathode exhibits a typical sensitivity of 60 μa/lumen when measured

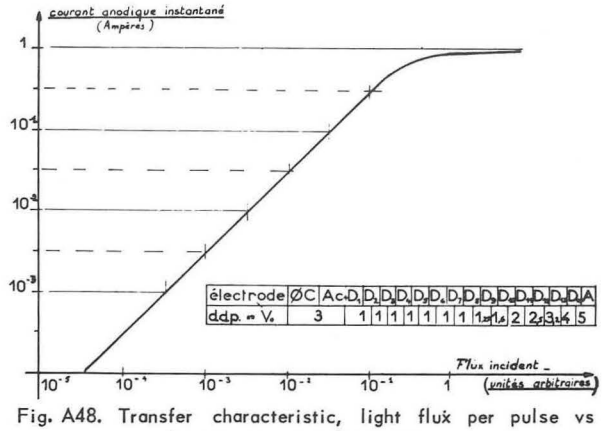

Fig. A48. Transfer characteristic, light flux per pulse vs instantaneous anode current.

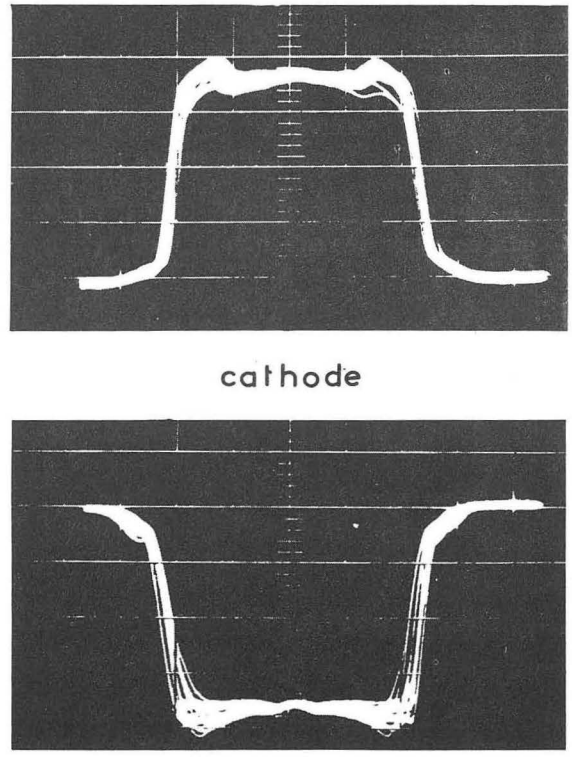

Fig. A49. Response of photocathode when excited by a flying-spot scanner; electron optics transfer characteristic.

with standard white A (2870°K). This corresponds to a quantum yield of 15% at the wave length of maximum response (4.000 to 4.2000 A). The homogeneity of the cathode and the uniform collection efficiency of the photoelectrons by the first dynode are demonstrated in Fig. A49. These pictures were obtained with a mechanical flying-spot scanner.[1]

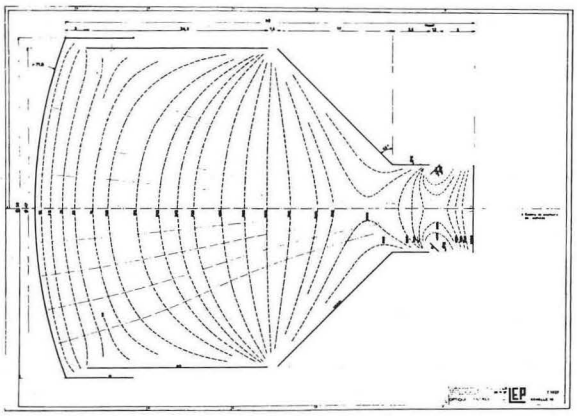

Fig. A50. Distribution of potential and electron trajectories, Type 204.

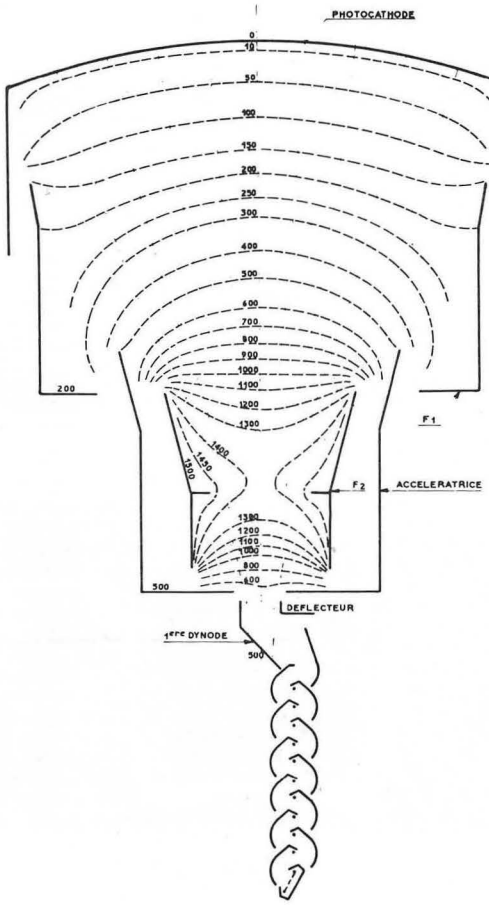

Fig. A51. Distribution of potential and electron trajectories, Type 206.

Although important, collection efficiency is not the only factor governing the design of the electron optics between the cathode and first dynode. Special attention was given to achieve "time focusing" at the same time as space focusing. Figure A50 shows the potential distribution and electron trajectories for the smaller tube, while Fig. A51 gives the same information for the larger tube.

"Time focusing," or the minimization of the dispersion in the transit time for different electron trajectories between the cathode and first dynode, was needed for two reasons: first, the lack of isochronism of electrons emitted from different parts of the photocathode but with assumed zero initial velocity; second, the lack of isochronism caused by initial velocities of electrons on a bundle of trajectories emitted from a given point.

Figure A52 shows the calculated values of the transit time for various starting points on the photocathode. Zero initial velocity is assumed with the electrode potentials given.

The effect of initial velocities can be seen from theory. The velocity component tangential to the cathode has a large effect on the space focusing but little effect on transit time. The normal velocity component has an opposite effect, with maximum influence on transit time. These conclusions hold to a first-order approximation, whatever the electrode configuration. The time-of-flight decrease is proportional to the square root of the initial kinetic energy and inversely

[1] Georges Pietri, J. physique, Suppl. A., Dec. 1958.

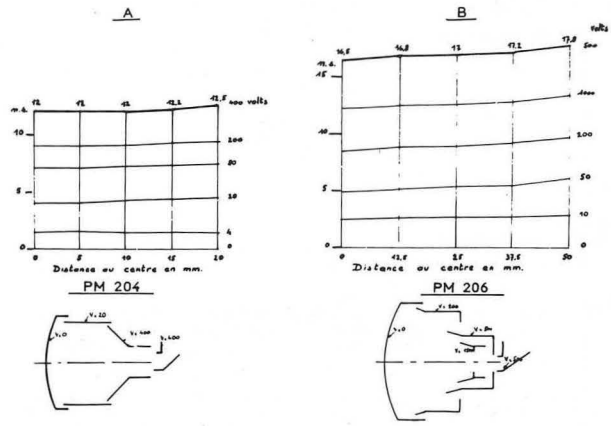

Fig. A52. Calculated transit time between photocathode and first dynode as a function of position.

proportional to the electric field at the point of emission.

The design of the electron optical system was based on the above consideration. The objectives were first, to obtain a uniform value of the electric field over the entire useful cathode surface, and second, to maximize this field for a given potential difference between the photocathode and the first dynode. These criteria have led to the following design. If we call the voltage of the most positive electrode in the optics V (in volts) then the field at the cathode is 0.1 V (v/cm) for the smaller tube and 0.035 V (v/cm) for the larger tube.

If V is taken, for instance, as 400 v for the first tube and 1200 v for the second, the field will be the same for both, namely 40 v/cm. As can be seen in Fig. A52, the curved photocathode, in conjunction with the shape and location of the focusing electrode, gives--as required--a field that is essentially constant over the whole surface.

The transit-time spread is given by

$$\Delta t = \sqrt{\frac{2m}{e}} \frac{\sqrt{\mu_0}}{E_0} \quad \text{(in cgs, emu),}$$

where μ_0 is the initial kinetic energy and E_0 is the field at the cathode; assuming as a mean value $\mu_0 = 0.4$ electron volt and $E_0 = 40$ v/cm, we see that the transit-time spread is slightly smaller than 0.5×10^{-9} sec.

At this time experimental data from users are becoming available on the smaller tube,[2,3] and this furnishes a good check on the calculations above. The large one has only recently come from the prototype stage and users' data are not yet available. But our own laboratory measurements are given in Fig. A53. These give an experimental check of the difference in transit time for electrons emitted from different parts of the cathode as shown in Fig. A52. No information is given on transit-time spread caused by initial velocities. The weak signal level on the first dynode prevents this phenomenon from being observed directly. It does appear in an indirect way, however, as a contribution to the rise time of the anode pulse.

Three factors can be distinguished as con-

[2] R. Meunier, L'Electronique Rapide en Physique de Hautes Energies, Industries Atomiques, 1958, No 5/6, p. 76.

[3] Y. Koechlin, Mesure de la Rapidité de Réponse du Photomultiplicateur LEP, type 204, Bulletin d'Informations Scientifiques et Techniques du CEA, 1958, No 23, p. 2.

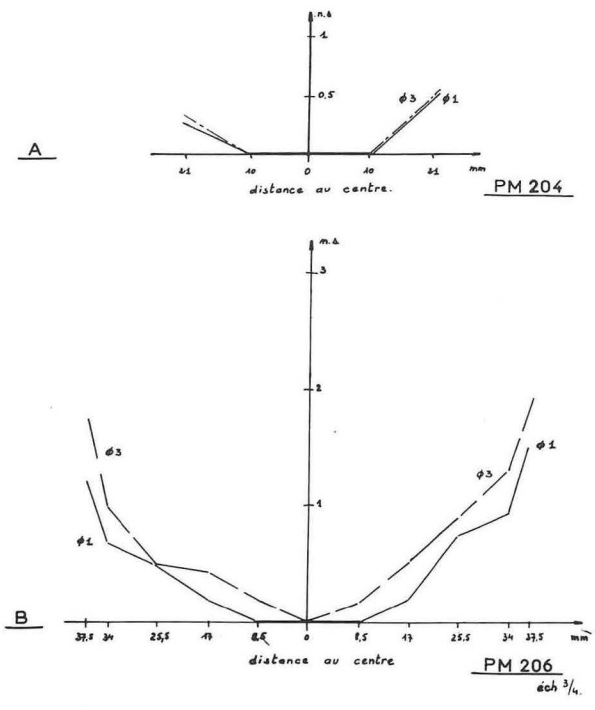

Fig. A53. Experimental curve relating transit-time dispersion to radial position.
A, Type 204; B, Type 206.

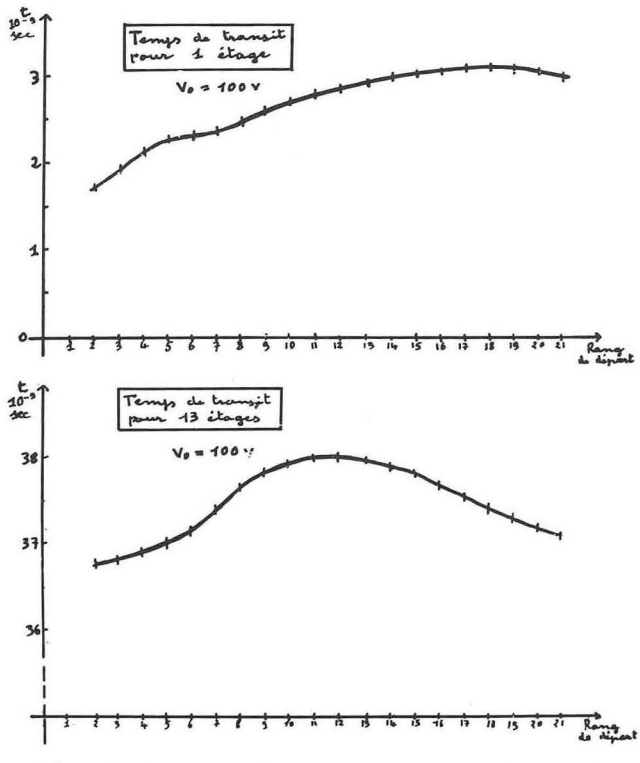

Fig. A54. Transit time through the dynode array. Above, single stage; below, 13 stages.

tributions to this rise time. These are the rise time of the electron pulse arriving at the first dynode, the time spread of different electron trajectories in the multiplier, and the displacement current in the anode lead during the whole duration of the ultimate electron transit from the last dynode to the collector.

For a single electron starting from the cathode (thermal noise electron, for instance), the first effect is absent. With the potentials and dimensions used in these tubes calculation shows that the displacement current lengthening of the rise time of the anode pulse is between 0.1 and 0.2×10^{-9} sec. This is quite negligible compared with the main effect, namely the trajectory spread through the dynode array.

Figure A54 shows the transit-time differences for different possible electron paths from one dynode to the next and through 13 stages, taking into account the partial compensation of short and long paths in succeeding stages. We must add to this geometrical time spread a contribution caused here also by initial velocity, in exactly the same way as for the photoelectrons.

In the actual case, for the dynode shape used, a typical value of electric field is $E_0 = 2\ V_0$ (v/cm), where V_0 is the voltage between successive dynodes (let us say 120 v as a typical value). In the secondary-emission case, however, the initial mean kinetic energy is of the order of 3 ev instead of 0.4 ev for photoelectrons. From these values a spread per stage of 0.25×10^{-9} sec is calculated. If the transit-time spreads combine according to a quadratic law, then a total spread of 0.9×10^{-9} sec is found. This is of the same order as the geometrical dispersion and leads to a toal calculated spread of 1.5×10^{-9} sec. Experimentally, in fact, the rise time and width at half height of the anode current pulse from thermal electrons or Čerenkov radiation is 2×10^{-9} sec.[3]

The above performance figures indicate the extent to which these photomultipliers may be used in nuclear timing experiments without impairing the time resolution of the experimental system.

A-5. A MILLIMICROSECOND LIGHT SOURCE

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Abstract

A fast light pulse can be produced by pulsing reverse current through a suitable silicon p-n junction. The light covers a range of photon energies from 1 to 3 ev. The immediate application is the testing of photomultiplier tubes, and, since any number of the junctions can be pulsed simultaneously, a method is available for lining up experiments in which large numbers of scintillators and coincidence circuits are used.

Introduction

Previous methods of obtaining fast-rising light pulses—such as the use of gas spark sources, mercury-switch arcs, or suitably baffled oscilloscope traces—suffer from the disadvantage that two or more of the sources cannot be turned on simultaneously. An additional disadvantage is the complexity of most of the schemes. In the work described herein currents were passed through a variety of solid-state materials in order to find a very simple light source which could be incorporated in scintillator-photomultiplier assemblies, both for the purpose of pulse-height calibration and for balancing out delays at coincidence circuits. The results obtained are so satisfactory that the method may find application in fundamental photomultiplier tube research.

Experimental Procedure

Voltages were applied to a wide variety of commercially available diodes and rectifiers in both the forward and reverse directions. Other junctions made from materials such as silicon and silicon carbide were tried. For most of the work, the voltage was a fast-rising pulse from a mercury switch and a coaxial cable. The switch was mounted to provide a source impedance of 50 ohms, and the output level was variable from 0 to 400 volts into a 50-ohm load. For some of the work dc biases were used in addition to the pulses. The diodes and crystals were viewed with a 6810-A photomultiplier tube with an S11 response. In several cases light was obtained. When no light was indicated the failure may have been due to the limited spectral response of the tube, but for the present purposes the only results of interest were those which gave the shorter wave lengths corresponding to S11 response. At present the best results have been obtained with silicon p-n junctions; therefore these results are described below. Photon emission from these junctions has been studied in detail by A. G. Chynoweth and K. G. McKay.[1,2,3]

The junctions as obtained from Dr. A. G. Chynoweth at the Bell Telephone Laboratories were formed by diffusing phosphorus to a depth of about 2 microns into the polished silicon surface.[4] The units were etched by using a wax mask so as to leave a circular island, as in Fig. A55. Electrical contacts were made by letting the crystal rest on a metal plate with a phosphor-bronze spring wire touching the n-type layer. The rectifier characteristic for one of the

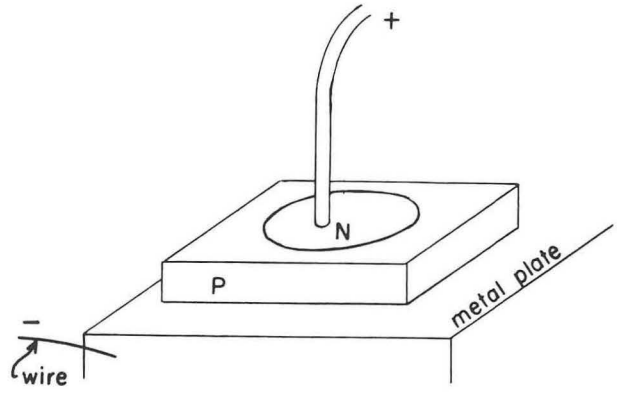

Fig. A55. The silicon crystal rests on a metal plate. Connection to the n-type layer is made with a spring wire contact. The crystal is approximately 1/8 by 1/8 in.

* This research is supported by the United States Atomic Energy Commission.

[1] A. G. Chynoweth and K. G. McKay, Phys. Rev. *102*, 369 (1956).

[2] A. G. Chynoweth and K. G. McKay, Phys. Rev. *106*, 418 (1957).

[3] A. G. Chynoweth and K. G. McKay, J. Appl. Phys. *39*, 1103 (1958).

[4] These junctions were very kindly obtained by Professor E. Burstein from Dr. A. G. Chynoweth of the Bell Telephone Laboratories at Murray Hill, New Jersey.

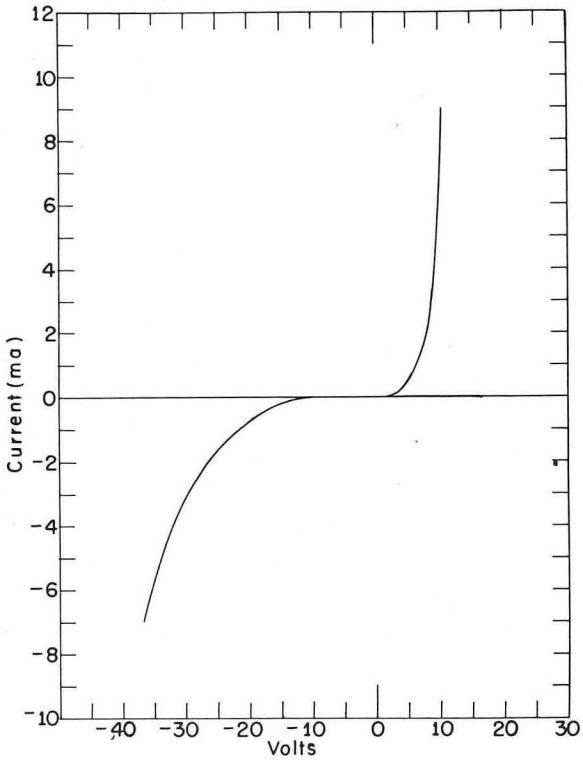

Fig. A56. Rectifier characteristic for the silicon p-n junction.

units is given in Fig. A56. A block diagram of the electronic apparatus is shown in Fig. A57. The pulser operated at 60 cps. Its rise time was known to be of the order of 1 mμsec. The voltage pulse at the crystal was put on one trace of the Tektronix 545 oscilloscope. Another trace was used for the output of the 6810-A tube. The amplifier, discriminator, and scaler were used to make measurements of the output pulse height. For the measurement of the rise time the output pulse of the 6810-A tube was passed along a 50-ohm cable to two cascaded Hewlett-Packard 460B amplifiers and then to the deflection plates of a Tektronix 517 oscilloscope. For the following

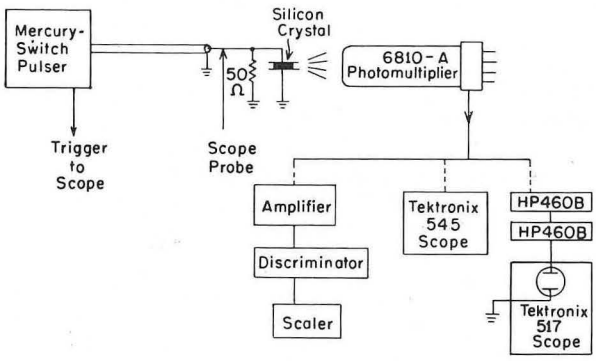

Fig. A57. Block diagram of the electronic apparatus for the various measurements.

results the crystal was about 1 in. away from the phototube cathode. No reflectors or collimators were tried.

Results

The rise time (10 to 90%) with the above method of viewing was about 5 mμsec. If the rise time of each amplifier is 2.6 mμsec and the rise time of the phototube is taken to be 3 mμsec and that of the pulser-oscilloscope combination is 1 mμsec, the system can be expected to have a response of about 5 mμsec. This means that the rise time of the light source itself is masked by that of the measuring apparatus. It may be tentatively set at less than 2 mμsec, but it should be emphasized that the ultimate speed could be well below this value.

To see how the output varied with the pulse level applied to the crystal, the voltage on the crystal was measured by the graticule of the Tektronix 545 oscilloscope. The photomultiplier anode current was integrated with a resistance of 50 K and the observed time constant was

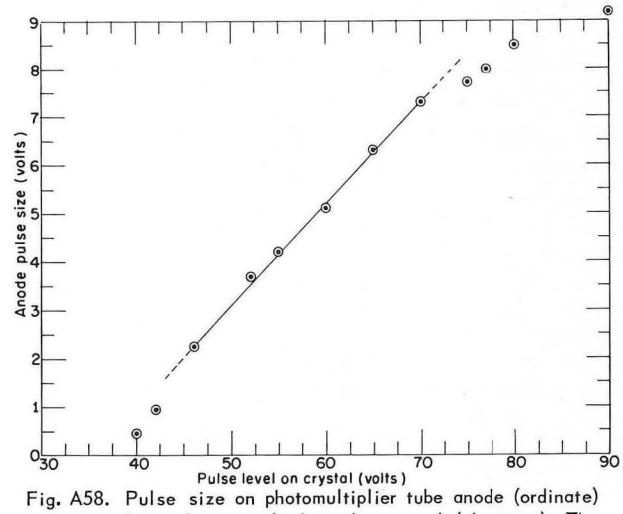

Fig. A58. Pulse size on photomultiplier tube anode (ordinate) vs pulse voltage applied to the crystal (abscissa). The errors on the measurements are about the size of the points.

36 μsec. This indicates a value for the anode-circuit capacitance of 66 μμf. The output was amplified, clipped, and then measured with the discriminator circuit. The results of measuring output vs driving voltage are given in Fig. A58. For this measurement the pulse duration was fixed at 0.5 μsec. The ordinate is the actual voltage at the phototube anode. It is seen that there is a reasonably wide range of output voltages for which the relationship with the driving pulse is linear.

It is possible to estimate from these data the

useful light output of the crystal. For the 7-volt pulse the charge at the anode is $Q = 7 \times 66 \times 10^{-12} = 460 \times 10^{-12}$ coulomb. This corresponds to 288×10^{7} electrons. The high voltage on the tube during this measurement was 2050 volts. From data published by RCA on this type of tube, the gain can be estimated to be about 1.6×10^{6}. This gives a value of 1800 electrons at the photocathode. The efficiency of conversion from photons to electrons depends, of course, on the photon spectrum. The spectrum obtained by Chynoweth and McKay [2] can be folded into the phototube-response function, and a conversion factor of 0.13 electron per photon at 4400 A can be used to normalize the result. A very rough estimate obtained graphically gives 0.10 electron per photon within the S11 range. This yields a value of 18,000 photons at the tube cathode. The solid angle subtended by the sensitive cathode area was about 40% of 2π, so that the source emitted about 45,000 photons over the wave lengths corresponding to S11 response. This figure may easily be in error by a factor of two in either direction because of the uncertainty of the tube gain, the crude method employed to find the photon-to-electron conversion efficiency, and the neglect of reflection at the air-glass interface of the tube.

The current per pulse through the crystal can be estimated from the effect of the loading on the pulse generator. For the 45,000 photons (as found above) it turns out to be about 9 amp, corresponding to 2.8×10^{13} electrons passing through the junction for the 0.5-μsec pulse. Now, Chynoweth and McKay estimate 10^{8} electrons per photon in the visible spectrum. On the basis of their estimate 280,000 photons should have been emitted at this current level. Again, the emission spectrum of the silicon crystal must be compared with the response of the phototube to see what fraction of the photons in the visible region would be detected. A rough estimate gives this fraction as 1/5, meaning 56,000 photons should have been obtained, whereas the above calculation gives 45,000. The excellent agreement with the Chynoweth and McKay result is fortuitous considering the numerous approximations made in obtaining the comparison.

Using the value of 1800 electrons at the cathode one should find the pulse-height response to have a full width at half maximum of $\sqrt{1800} \times 100/1800$, or 2.3%. The measurement of this was made, and the result is presented in Fig. A59. The scale of the absicssa has changed, but the above estimate of the number of electrons applies to this measurement as well. The pulser voltage was fixed at 70 volts, which seems to be about

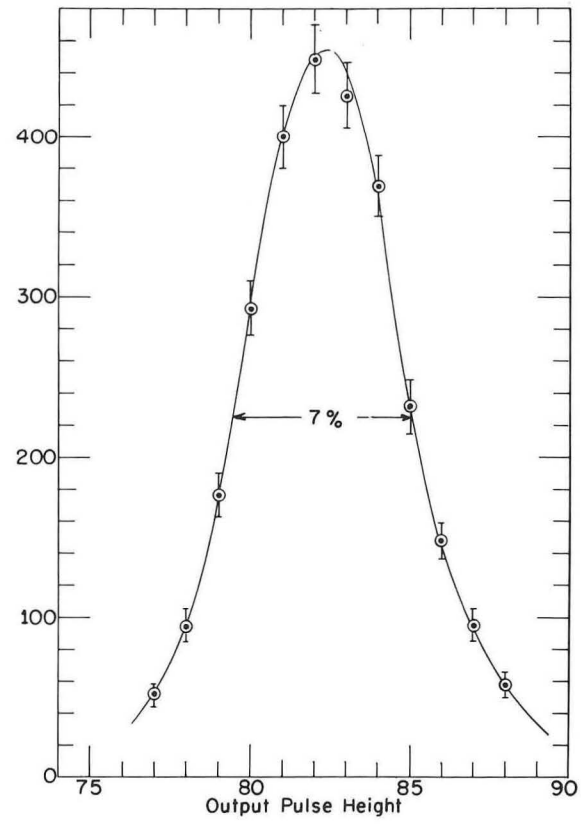

Fig. A59. The output pulse-height-distribution curve for a constant pulse voltage applied to the crystal.

the end of the linear range of crystal light output. The resulting curve had a full width at half maximum of 7%. Therefore the crystal output can be considered to have a 6.5% width at this level of operation.

Discussion of Results

Chynoweth and McKay [1,2,3] have shown two mechanisms to be operative in the emission of visible light from silicon p-n junctions. In one case carriers are generated by avalanche breakdown, and then, after being accelerated by the junction field, they recombine. In the other case, the carriers are the result of internal field emission. In avalanche breakdown the light emanates from a great many localized microplasmas which are concentrated around the junction edge. (See, for example, the photographs by Chynoweth and McKay.[3]) Each microplasma passes a current of about 100 μa. The number of microplasmas increases with the breakdown current while individual microplasmas remain at the same intensity. To the eye, the individual spots appear white or yellowish white. At low breakdown currents a dull red glow is seen over the entire junction.

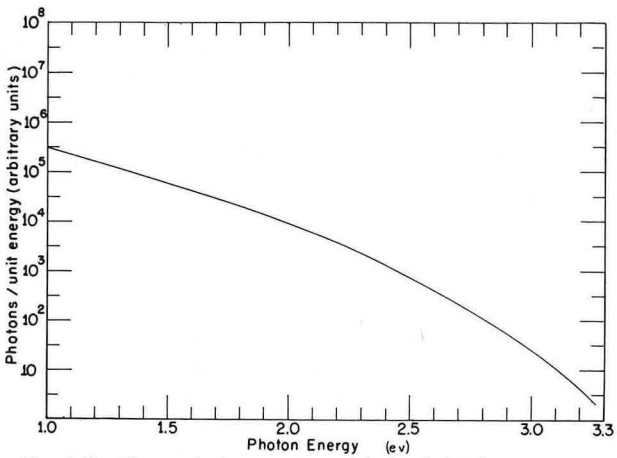

Fig. A60. The emission spectrum of the light from reverse current through the junction.

This latter is characteristic of the field-emission mechanism. The emission spectrum of the light from avalanche breakdown as measured by Chynoweth and McKay is reproduced in Fig. A60.

The rate at which the voltage on the crystal rises depends, of course, on the capacity of the junction. The capacity in turn depends on the voltage, because the junction becomes wider as the voltage increases, and, since the resistance is also a function of the voltage, the differential equation for the rise of the avalanche current is rather complicated. With fast-oscilloscope viewing it should be possible to partially "tune" the capacitance of the junction to improve the rise. Also a dc bias would improve the rise time at the expense of background light. Evidence from the microwave noise spectrum indicates that the individual microplasmas turn on in a time of the order of 10^{-11} second.[5] Therefore it may be possible that until this limit is reached the ultimate speed with which the light output can be made to rise may be limited only by the experimenter's ingenuity in getting the voltage across the junction to rise. In this connection it is noteworthy that the crystals employed in this work had the worst possible geometry. The perimeter-to-area ratio of the junction, and hence the light output per unit of capacitance, can probably be improved a hundredfold by making line junctions with essentially no area.

In the plot of the light output vs driving voltage, the saturation can be tentatively explained by assuming that all the possible microplasma locations at the perimeter are conducting when the impressed voltage is sufficiently high. Further breakdown sites are along dislocations throughout the junction area. The light from these, however, traverses a thin layer of silicon and suffers considerable absorption. Again the circular shape is the poorest, so that the linear part of the light yield could be greatly extended by the increased perimeter available with other shapes.

It is hoped that the light sources can be encapsulated in the small glass containers in which commercial diodes are commonly sealed. In this way, they could be mounted on photomultiplier tubes along with the scintillator. The protruding leads would go to a connector which would receive the test pulse.

If the units are to be used for pulse-height calibration, careful attention must be paid to temperature effects. Initial indications are that there is no pulse-height change over the commonly encountered laboratory temperature ranges, and Chynoweth and McKay have measured the emission spectrum over a wide temperature range and find it to be quite insensitive.

Acknowledgments

It is a pleasure to express appreciation to Professor E. Burstein for discussions concerning the mechanism of light emission. Thanks also to Professor J. Halpern for many suggestions, and particularly for the encouragement to carry out this work; and to Dr. A. G. Chynoweth of the Bell Telephone Laboratories for an interesting discussion and for making the silicon p-n junctions available.

Discussion

Question: What voltage was applied to the junction?

Whetstone: I had an 800-volt power supply for the pulser, but the mismatch was so bad that I got only 70 volts across the junction, whereas with 800 volts applied one should get out 400 volts into a 50-ohm load. The low voltage is due in part to the high capacitance of this geometry. You could go to lower-impedance pulsers, but I think the answer is to go to different shapes.

There's a question about the commercial availability. The Research Department of Bell Labs is very cooperative. I haven't had contact with the Development Department. We must have somebody who can diffuse these junctions into the desired shapes.

[5] A. G. Chynoweth, private communication.

These exist only in a research laboratory. They're not in the development stage. My own hope would be to make a junction like this and put it in a small glass capsule (like germanium diodes) with two wires coming out. Then we could just place one of these things under the tape when we want to put scintillators on phototubes.

Question: Does the light start immediately as soon as the pulse reaches the junction?

Whetstone: Well, I can't tell how much delay is in the phototube and cables and things like that. Since it has a fast rise, I presume it starts immediately.

B-1. THE USE OF ELECTROSTATIC STORAGE TUBES FOR FAST NUCLEAR-DATA STORAGE

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Introduction

Multichannel data recording for neutron time-of-flight and pulse-amplitude analysis is now a well-established technique, and many instruments are in use. The number of events that such equipment can analyze and record is limited by the dead time after each input pulse; this time may be about 20 μsec for magnetic-core storage or between 1 and 5 msec for magnetic-tape recording. Thus when such instruments are required for use with high-energy acceleration machines the instrument dead time limits the average rate for analysis to about 1 pulse per machine burst. In order to increase this input information rate it is necessary to have data-analysis equipment with a dead time of only 1 or 2 μsec. One method of obtaining such an instrument is to use a barrier-grid storage tube which can accept, analyze, and record data quickly during the period of one accelerator pulse. After this pulse all the stored data are taken from the storage tube and re-recorded on a more permanent instrument, such as a magnetic-tape store. The storage tube is then ready to accept information from the next accelerator pulse.

An instrument using a storage tube in this manner is being developed by Mr. Kandiah at the Atomic Research Establishment, and this will be used in conjunction with the existing slower multichannel data-recording instruments.

Speed of Recording on Storage Tube

Figure B1 shows the principle of operation of the tube. The electron beam charges the insulator surface where it impinges, and the voltage tends to stabilize at the grid potential. The writing process consists of holding the target anode at a potential of about -50 v and then switching on the beam at a defined position on the target area where it is required to store a "bit" of information. This portion of the target surface then changes its voltage towards grid potential, thus applying charge to the element of capacity formed between the target plate and the insulator surface (where the beam is falling). The number of discrete portions of the target area upon which information may be written is limited by the spot width of the beam, and for existing tubes corresponds to about 200 bits each in X and in Y direction, or a total of 40,000 (the extreme limiting condition).

The reading-back operation consists of switching the target anode back to grid potential and then scanning the target area slowly with the beam. The beam will then discharge any area on which a charge has previously been written, so that if a suitable circuit is arranged to detect this change of target voltage (or charge) the stored information may be recovered. The usual type of circuit in which both grid and target anode are kept at high impedance with respect to earth has been found unsatisfactory for short-pulse recording, as the minimum pulse duration (time of beam current on) is about 1 μsec. This is because of various voltage disturbances in the

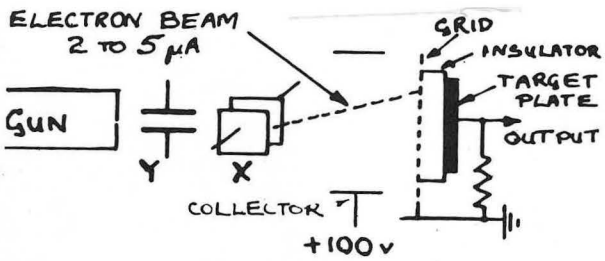

Fig. B1. Barrier-grid storage tube.

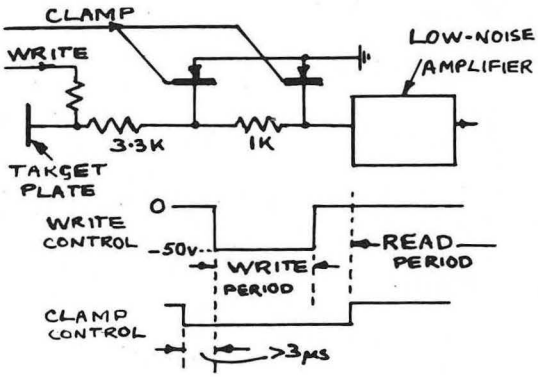

Fig. B2. Reading from barrier-grid storage tube.

tube due to the presence of the grid wires and other causes.

The circuit shown in Fig. B2 is an improved arrangement analogous to a grounded-grid triode. The grid is grounded and during the "read" time the target anode voltage wave form corresponds to the change in charge of each element of target insulator. With this arrangement it is found that there is little "disturb" voltage background, and a minimum recording-pulse duration of 0.1 μsec may be detected, giving a good signal-to-noise ratio. The amplitude of the output pulse is small, so that a low-noise amplifier is necessary. This takes the form of a low-noise input thermionic valve followed by a transistor pulse amplifier.

Figure B3 shows the general arrangement of a 1024-channel "time-of-flight" recording instrument. The ten-stage binary scaler is reset to zero and then scales the input timing pulses defining the timing channels. This action scans the beam in a step fashion across the face of the tube; there are 32 beam positions along each line and 32 lines, giving 1024 possible beam positions or "addresses." The beam is normally off and is switched on for only 0.1 μsec when a neutron pulse or other event to be recorded is received. This beam brightening is timed to occur about halfway between two adjacent timing pulses, so that the beam is stationary during this writing phase.

At the end of the writing period the storage tube is switched to the "read" cycle, the scaler reset, and beam switched on. Pulses of low recurrence rate are then fed into the scaler and so each address on the storage tube is rescanned. When a stored pulse is detected the scaler is stopped at this address and the timing information or scaler setting is transferred to a permanent-storage instrument such as a magnetic tape. As soon as this transfer is complete the storage-tube scaler is allowed to continue its scanning operation until all the stored pulses have been read, at which time the instrument is restored to the "write" position and is ready for the next burst of information from the accelerator machine.

The time taken to write a neutron pulse consists of the 0.1 μsec required by the tube plus a suitable period for the circuit operations. This total period is about 0.5 μsec, so that it is considered that the instrument will be designed for performance with 1 μsec dead time (a safety factor of 2 has been inserted). This time is several periods of the timing pulses, and circuits must be included for stopping the beam on the required position for 1 μsec and then subsequently correcting the timing scaler for the lost timing pulses.

It will be noted that only 1024 timing channels have been used instead of the theoretically possible 40,000. This reduction is to allow an adequate factor of safety to ensure that there is no difficulty in registration between writing and reading scanning of the target face.

One other application of the tube is to record the amplitudes of pulses; this will be done by making the Y deflection proportional to peak pulse amplitude. The X step scan will then allow the storage of 32 such pulses during one write period or accelerator-machine burst.

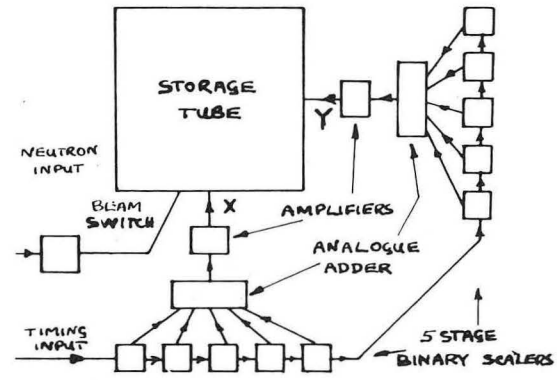

Fig. B3. Fast nuclear-data storage with barrier-grid storage tube.

B-2. ANALYSIS OF MILLIMICROSECOND PULSES BY USE OF A CHARGE-STORAGE TYPE OF PULSE-HEIGHT ANALYZER*

Louis Costrell and R. E. Breuckmann
National Bureau of Standards, Washington, D. C.
Presented by Louis Costrell

We have been working on a charge-storage type of pulse-height analyzer for use with pulsed accelerators, with the intention of producing an analyzer that can handle several pulses in a single short burst. This is of importance in increasing the efficiency of operation of pulsed accelerators because of the low duty cycles at which these machines operate. The low duty cycles (frequently a small fraction of a percent) make the accumulation of energy data extremely slow unless the machines are operated at very high pulse rates during their active periods. Cunningham first suggested that advantage be taken of the relatively long dead time available between bursts for leisurely analysis of pulses occurring during the bursts.[1] Reaves[2] proposed a modification of Cunningham's system and Pieper[3] has also described a system of this type. The charge-storage analyzer on which we are working is described in Nuclear Instruments.[4]

Our interest has been in pulses of about 1/2-μsec duration and a time resolution of about 2 μsec for use with NaI(Tl) crystals. However, fast scintillators permit much shorter resolution, the full utilization of which would necessitate much faster pulses. We have therefore tried to get some idea of how the basic system will operate with pulses as short as 2 mμsec. It should be emphasized that this work with fast pulses is of a preliminary nature and that the limited results presented are indicative rather than conclusive.

At this point, the question naturally arises as to what we mean by a charge-storage type of pulse-height analyzer. We will briefly describe the system for which we have coined this title. The heart of the analyzer is a cathode-ray tube (Fig. B4) in which the pulses to be analyzed are applied to one of the vertical deflection plates. As the electron beam travels along the phosphor, it ejects secondary electrons, leaving a line of charge on the phosphor. A pickup plate made of thin transparent plastic on which a semitransparent layer of nickel has been evaporated is secured to the outside face of the tube.

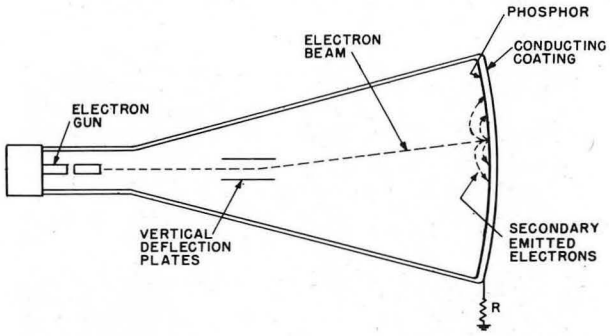

Fig. B4. Cathode-ray tube used as charge-storage–type pulse-height analyzer.

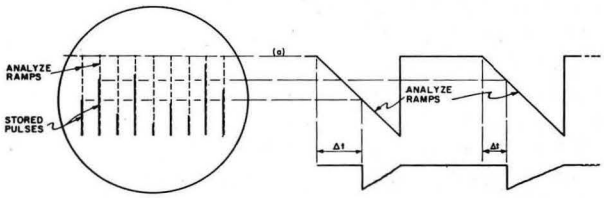

Fig. B5. Charge-storage system, showing storage and analysis of nine pulses. The analyze ramp detects the charge discontinuity at the top of the stored pulse. The time interval Δt is a linear measure of the amplitude of the stored pulse; a short interval corresponds to a high-amplitude pulse and a long interval to a low-amplitude pulse.

This plate serves as one plate of a capacitor; the tube phosphor is the other. During the dead interval between bursts, an "analyze" ramp is applied to one of the vertical deflection plates, sweeping the electron beam over the phosphor. The analyze ramp causes secondary electrons to be emitted from the phosphor, the rate of emission at any instant being dependent on the

* This work was supported by the United States Atomic Energy Commission.

[1] J. A. Cunningham, National Bureau of Standards Report NBS-3258, 1954.

[2] J. H. Reaves, Nuclear Instru. 2, 136 (1958).

[3] G. F. Pieper, Paper presented at International Symposium on Nuclear Electronics, UNESCO House, Paris, France, Sept. 1958.

[4] L. Costrell and R. E. Brueckmann, Nuclear Instr. 3, 350 (1958).

amount of charge present at the particular point being scanned. The change in phosphor potential is capacitatively coupled through the pickup plate to the pickup-plate amplifier.

Figure B5 shows the storage and analysis of nine pulses during a burst. After a pulse has been stored, a beam-storage-tube type of staircase generator steps the electron beam a fixed amount horizontally to a position where it awaits the next pulse in the burst. The staircase generator used can handle up to nine pulses per burst. After it has received this amount, it is unreceptive to additional pulses in the same burst. The loss in counts due to the limit in the staircase capacity is about 1% at an average pulse rate of 5 per burst. The loss at other pulse rates is shown in Fig. B6. The storage capacity can be readily increased by the use of an additional beam-switching tube, though this was not warranted in our application.

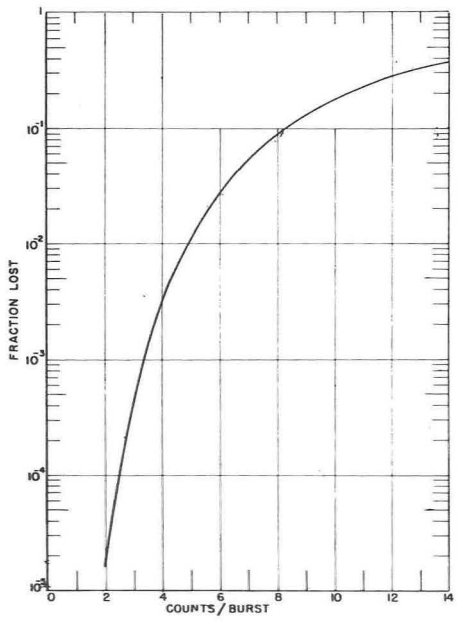

Fig. B6. Pulses "lost" because capacity is nine pulses per burst.

During the dead interval between bursts, analyze ramps, positioned horizontally by the same staircase generator used in storing the pulses, sweep down the tube as shown in Fig. B5 until they detect the charge discontinuity produced by the peak of the stored pulse. When the ramp detects the discontinuity, a pulse is produced at the pickup plate. It will be noted from Fig. B5 that the time interval from the beginning of the analyze ramp to the output pulse is a linear measure of the amplitude of the stored pulse, a short interval corresponding to a high-amplitude pulse and a long interval to a low-amplitude pulse. The pulse amplitude has thus been converted to a time duration and is handled as in other pulse-height-to-time conversion analyzers and stored in a magnetic-core memory array.

The signal at the pickup plate is shown in Fig. B7. The sweep speed is 50 μsec/cm. In the upper trace, pulses being stored are visible between 70 and 110 μsec. They are seen more clearly in the lower trace, which is the same as the upper trace except that the vertical-deflection sensitivity has been increased. The pulse at 320 μsec marks the beginning of the pickup-plate amplifier gate. The analyze ramp starts 6 μsec prior to this pulse. The signal output pulse is at 390 μsec. The output of the pickup-plate amplifier is shown in Fig. B8. The block diagram of the analyzer is shown in Fig. B9 and the timing sequence in Fig. B10.

Figure B11 shows a Cs^{137} spectrum taken with the analyzer using a 6810 photomultiplier and a 2x2-in. cylindrical NaI(Tl) crystal. The 662-kev

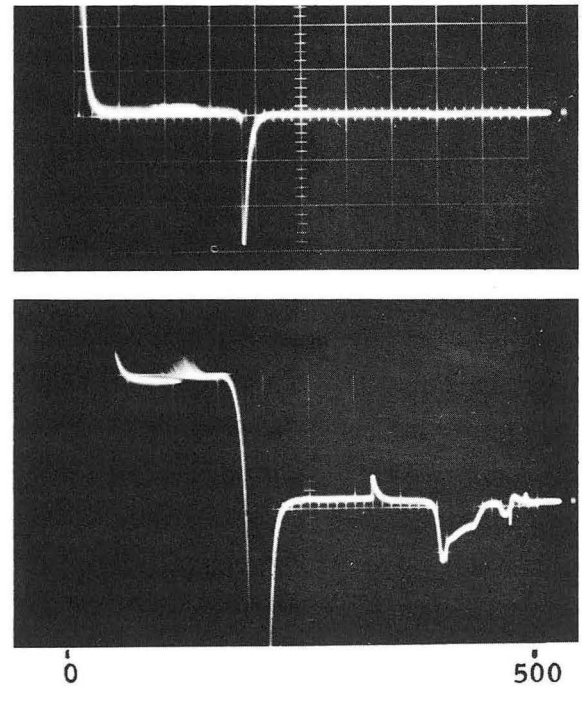

Fig. B7. Pickup plate output. Sweep speed 50 μsec/cm; sensitivity 0.3 v/cm, upper trace; 7 mv/cm, lower trace. The large pulses at the beginning of the trace and at 180 μsec are due to the beginning and end of the storage gate. The small pulses between 70 and 110 μsec are pulses being stored. The pulse at 320 μsec marks the beginning of the pickup-plate amplifier gate. (The analyze ramp starts 6 μsec prior to this pulse.) The signal output pulse is at 390 μsec.

photopeak is at the left and the 32-kev barium x-ray peak at the right. Figure B12 shows a spectrum taken with the analyzer of scattered radiation from a synchrotron with a 100-μsec burst duration. The curve was taken at 5.6 pulses per burst. The circles represent data taken at 1 pulse per burst, normalized at the peak for comparison with the curve.

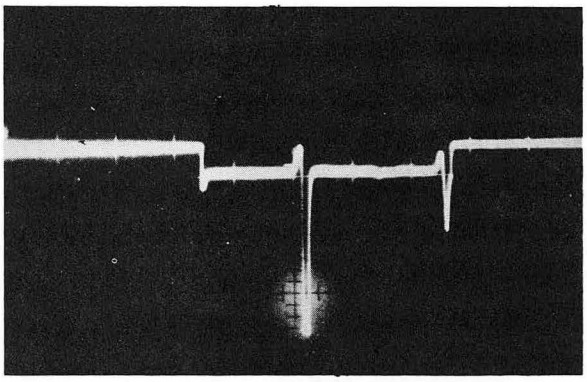

Fig. B8. Output of pickup-plate amplifier.

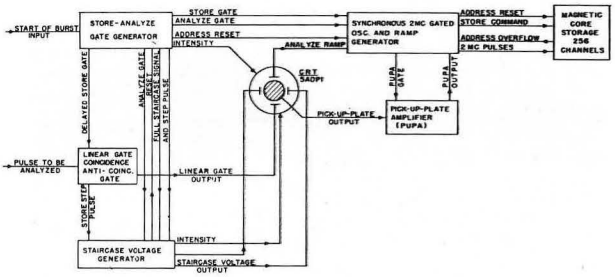

Fig. B9. Block diagram of charge-storage analyzer.

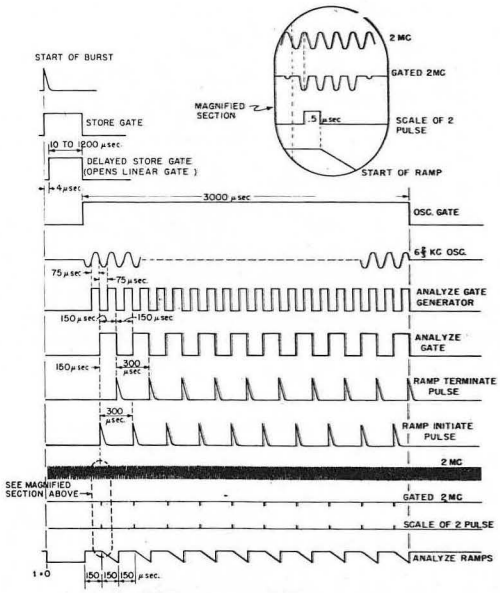

Fig. B10. Timing sequence diagram.

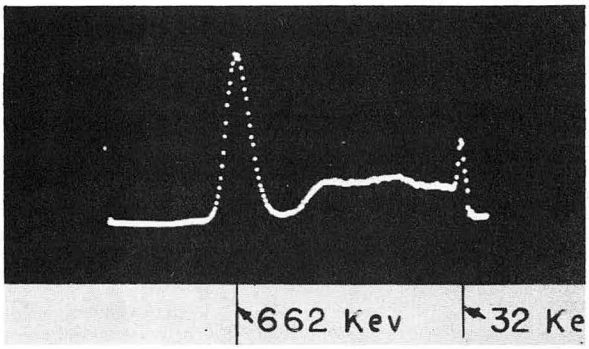

Fig. B11. Cesium-137 spectrum taken with charge-storage analyzer. The 32-kev barium x-ray peak is at the right.

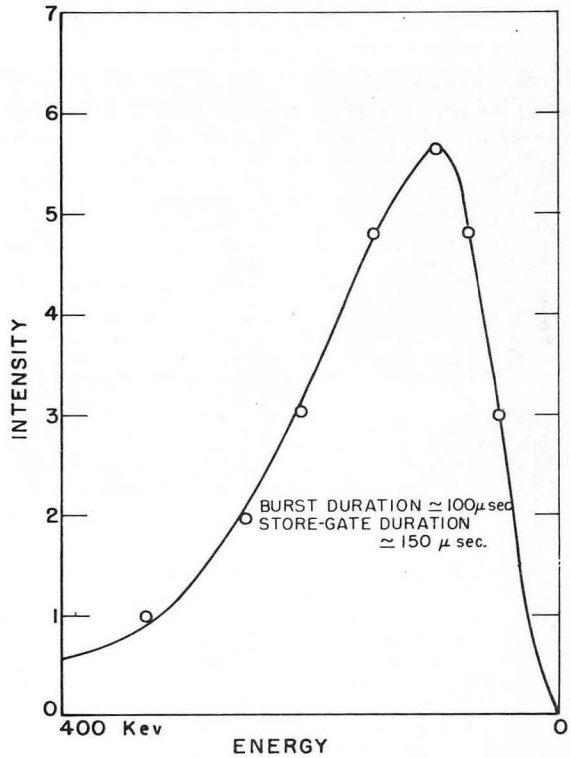

Fig. B12. Spectrum of scattered radiation from a synchrotron with a 100-μsec burst duration. The curve was taken with the charge-storage analyzer at 5.6 pulses per burst. The circles represent data taken at 1 pulse per burst, normalized at the peak for comparison with the curve.

To obtain data on the analysis of millimicrosecond pulses, the linear gate was omitted and the arrangement shown in the block diagram of Fig. B13 was used.

Figure B14 is the output of the pickup plate for a 5-mμsec pulse. The vertical deflection sensitivity is 1/4 mv/cm and the sweep speed is 5 μsec/cm. The output pulse (near the center of the trace) is about 1 mv in amplitude, as compared with about 10 mv for a pulse of long duration.

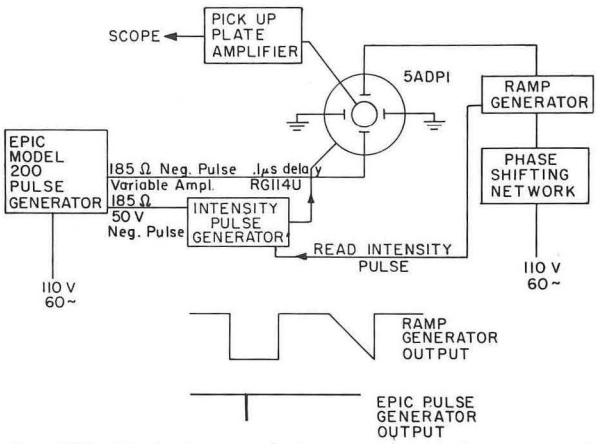

Fig. B13. Block diagram of charge-storage analyzer as used for millimicrosecond pulse data.

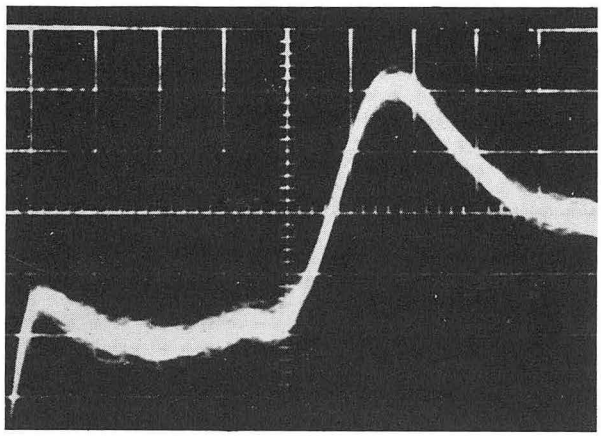

Fig. B14. Output of pickup plate for a 5-mμsec pulse. Deflection sensitivity 1/4 mv/cm, sweep speed 5 μsec/cm. The output pulse (near the center of the trace) is about 1 mv in amplitude.

Figure B15 is for a 2-mμsec pulse. The deflection sensitivity and sweep speed are the same as for Fig. B14. It will be noted that the signal-to-noise ratio is about half of that obtained for a 5-mμsec pulse, and introduces an uncertainty in pulse location of about ± 0.7 μsec, which corresponds to a jitter of about ± 0.7% of full scale.

The data that we have taken on millimicrosecond pulses have been obtained by direct measurement of the pulse location on photographs similar to Figs. B14 and B15, since our pickup-plate amplifier was not designed for millimicrosecond pulse applications. It should be noted also that the staircase generator is too slow to take advantage of the short pulse spacing than can be used without pile-up with millimicrosecond pulses.

Figure B16 shows results obtained with pulses of 2, 5, 25, and 100 mμsec duration. It will be noted that the ordinate is the pulse-generator reading. The actual input amplitudes are a function of the pulse duration and the 2-mμsec integrating time constant at the analyzer input. If the input amplitude is calculated (with due consideration to the uncertainties in the input time constant and pulse durations), and Fig. B16 replotted with input amplitude for the ordinate, the curves for the 2-, 5-, and 25-mμsec pulses will be essentially coincident over much of their range. The curves are apparently linear except that for input amplitudes below about 10 volts the curves for the 2- and 5-mμsec pulses become nonlinear. These nonlinearities have not yet been investigated.

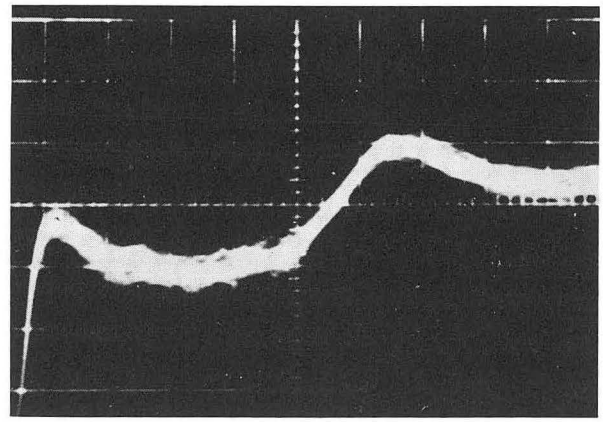

Fig. B15. Output of pickup plate for a 2-mμsec pulse. Deflection sensitivity 1/4 mv/cm, sweep speed 5 μsec/cm. The output pulse (near the center of the trace) is about 1/2 mv in amplitude. The noise introduces an uncertainty in pulse location of about ± 0.7 μsec.

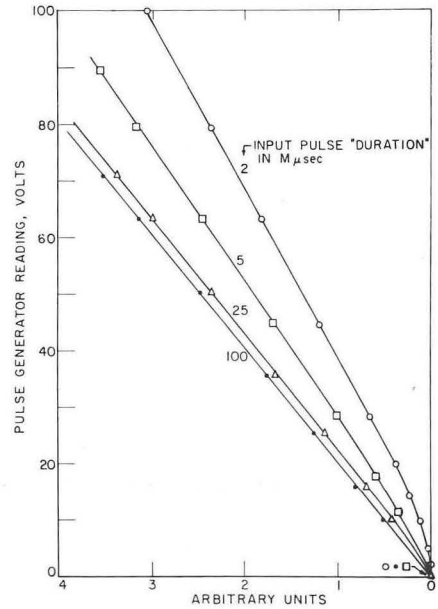

Fig. B16. Response of charge-storage analyzer to millimicrosecond pulses.

Discussion

Costrell: There was a question regarding resolution. If we are dealing with pulses of 1/2 μsec, such as those that we have played with the most so far, 0.7% resolution for pulse-generator pulses would be poor. On the other hand, for 2, 5, and 10 mμsec, I would be extremely reluctant to quote any sort of figure on resolution. I merely said that there is this much uncertainty in locating the position of the pulse when looking at the photograph. And I didn't say to what extent this uncertainty would be increased. It can only be increased, not decreased, by the succeeding electronics.

Question: Have you had trouble with astigmatism?

Costrell: We haven't noticed anything serious along this line yet. There is more possibility of trouble in this with the millimicrosecond pulses than there is with microsecond pulses. The reason is that with microsecond pulses we have been working push-pull, whereas with millimicrosecond pulses we have been working the deflection plates single-ended, which necessitates use of a keystone correction.

Question: In using a 5ADP1 cathode-ray tube does the coarseness of the phosphor have anything to do with the signal-to-noise ratio?

Costrell: I have no idea.

Wiegand: I would like to say that I think the session should be rather informal and that the speakers need not confine themselves to apparatus that has been perfected, but also mention what you would like to have developed. That's one of the purposes of this conference, to bring together many ideas so that we can learn what the trends are — which should be a help to all of us. So we need to say what we expect in the future of these developments.

Question: How does the DADP1 erase the information?

Costrell: As in normal Williams tube storage, the reading immediately causes the erasure.

Roberts: Is any work being done to establish systems that can accumulate more than nine pieces of data per burst?

Costrell: This is a rather simple extension as far as our system is concerned. It would have been a very simple matter to go beyond nine. We used a ten-stage beam-switching tube in which we used the tenth step for other purposes. If it would have served a real purpose we could have added another beam-switching tube. My understanding is that Pieper in his work at Yale is dealing with more than nine. We had no reason to do so.

Patten: Can you store more than 500 bits of information on such a system—500 per μsec?

Costrell: At this stage of the art, we cannot do so in 1 μsec.

Wiegand: Don't forget that Dr. Wells is still here and available for questions, if we want to get him in on the discussion.

Wells: Is the spot size small enough to get 500 dots side by side?

Costrell: I seriously doubt it. I know one begins to run into trouble between adjacent pulses at much less spacing that this would make available.

Question: Could you explain a little more about the actual mechanism of the storage?

Costrell: While the beam is sweeping along the phosphor it causes ejection of secondary electrons, leaving, in essence, a line of charge along the phosphor. There are two things that can happen to the electrons. They can either be collected along the edge of the tube, or they can be deposited in potential rows alongside the line of charge. Now, when a reading beam comes along, it traces over the same path and also ejects electrons, but the number of electrons ejected depends upon the charge condition along this line. A charge discontinuity is encountered at the top pulse.

Wiegand: Dr. Wells may want to add something to that.

Wells: It is rather different, as I said, in beam-storage tubes, in which the secondaries are collected by the barrier grid.

(Mention was made that other laboratories, including Columbia, Yale, and GE, are working along this line.)

Wiegand: I'm glad to see these ideas on data storage appearing, because from the viewpoint of some of the physicists who are using the giant accelerators, it is becoming more and more apparent that our counters and counter systems are growing more complicated, and as

I see it at this time, it seems that we will have more and more counters. Our arrays will have smaller and smaller elements. In order to take more efficient advantage of the beams that the high-energy accelerators are producing, it will be necessary to live with this complication so that we can analyze reactions that involve many particles.

We have had the experience at this laboratory of recording so many pulses on oscilloscope traces that it took literally months and months to read and analyze the data. As we already have our data in electrical impulse form, it appears more and more imperative that we take advantage of this fact and be able to store the data and feed it into computers that can sort the information and tell us the answers to the questions we would like to know—such as In what direction did the particles go?—How many of them? and so forth.

We who work with high-energy machines are extremely interested in data-storage systems, and hope they will be developed to a high degree of perfection.

The arrays of counters will become, as I say, more and more complicated, with smaller and smaller elements, until eventually one of these days (I think reasonably soon), we will be down to the point where we will get a view of the events in filament chambers, and finally some day, perhaps, we shall view the tracks in a scintillation material. Then, of course, the amount of information will really require a computer.

In connection with the discussion on charge-storage methods which we concluded a few minutes ago, I hear from reliable sources that a commercial company called The Radiation Instrument Development Laboratory of Chicago is planning to bring out a charge-storage device in a barrier-grid tube. This device can store 100 pulses with a resolution of 10 μsec, and it's fitted to go onto 100-channel pulse-height analyzers. This device may be out in a year and cost $30,000. We can show them some interest in it, perhaps. The person to inquire of there is Jerry Wolfe. I mention this in case people are thinking of these devices.

B-3. REVIEW OF IMAGE INTENSIFIERS

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The primary use of image intensifiers in nuclear physics will be for viewing scintillation chambers, in order to provide a powerful research tool which will have both good time and good space resolution. Let us, then, first briefly describe a scintillation chamber system in order to make more clear the requirements placed on image intensifiers for this use.

Figure B17 is a block diagram of the necessary components of a scintillation chamber system. The chamber itself may be simply a block of scintillating crystal, or else an array of scintillating fibers, stacked in alternating layers so that light from an ionizing particle passing through the chamber will be piped along the fibers to two faces. Thus the path of the particle is projected onto two 90° stereo views, and two light-amplifying systems are then required to see these two projections.

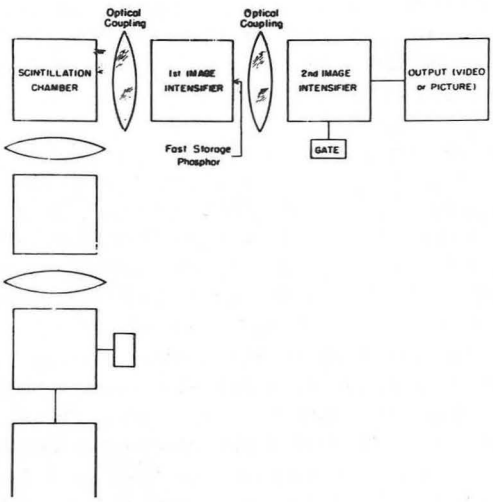

Fig. B17

In either of the two light-amplifying systems, the first element is an optical coupling between the chamber and the first image intensifier. For many applications of the device, it is the procurement of just this element which is the chief stumbling block to a practical scintillation chamber. In order to achieve a useful signal-to-noise ratio at the photocathode of the first image intensifier, it is essential that these optics be extremely fast. On the other hand, for most applications, the chamber must be large (say, 5 in. on a side), and hence a very large field is required in the optical system. While suitable Schmidt optical systems have been designed for chambers even as large as 5 in., these are expensive (e.g., $15,000), and are of such a form that they preclude the use of a magnetic field on the chamber. It is possible to use refractive optics if the optical system demagnifies, but then much more severe restrictions are placed on the resolution of the image intensifiers. A very nice solution would be to couple directly to a glass-fiber faceplate on the back of which is the photocathode of the first image intensifier, but these are expensive (e.g., $5,000 for a 5-in. faceplate) and have so far not been produced vacuumtight in bundles larger than 1 in. in diameter, although it is hoped that 5-in. ones will shortly be available. However, the problems of sealing the faceplates in the intensifiers and of depositing a photocathode on the lead glass (which cesium attacks) of the faceplates have not yet been solved. Perhaps the most desirable solution of the optical coupling problem would be to make the faceplate of the image intensifier sufficiently thin so that direct coupling is possible without appreciable loss of resolution. This, of course, means that cathodes of reasonable size would have to be internally supported.

Let us see next what additional requirements are placed on the first image-intensifier stage, other than that the photocathode be large (say, at least 5 in. in diameter), or that the resolution be very good (say, 20 lines per mm for a 1-in. cathode), in order that one may couple it to a chamber of useful size. One requirement is that the photocathode be of as high an efficiency and as low a noise as possible, since one would like to be able to detect single, or at best a few, photoelectrons. The use of a multialkali surface thus seems advisable at present, and its use makes easier the next requirement: that the quantum gain of the tube be at least 100, in order that the image not suffer from statistical fluctuations at the next photocathode, after the optical-coupling loss. This gain can be almost an order of magnitude less if the second stage is contained in the same en-

velop as the first, so as to avoid most of the loss due to optical coupling. It should be noted that the gain referred to is quantum gain, since demagnification provides no increase in brightness if one deals with single photoelectrons. However, demagnification may be very beneficial in that it makes subsequent optical coupling simpler, provided resolution is maintained.

One essential feature of the first stage is that it have a phosphor for fast storage. Although the first stage must be on at any time that an event may occur in the chamber, the second stage must be kept off until the desired event takes place. At that time, the second stage is quickly gated on (and the first stage preferably gated off), so as to look at the desired event as it appears on the phosphor. After the image of this event has faded from the phosphor, the second stage is again turned offf. At present, the most desirable storage phosphor appears to be P15, which has a decay time of about 10^{-6} sec. However, as gating improves, one will probably want to use P16, or possibly even faster phosphors.

Because there is either optical or electrical demagnification in the first stage, the second optical coupling is less of a problem than the first. However, even here fiber faceplates seem the most desirable solution. If Schmidt optics are used, it is helpful to have the curvatures of the first phosphor and second photocathode the same. Lens optics are of course considerably simplified if the photocathode is flat rather than convex, as it usually is.

The second image intensifier indicated in Fig. B17 may actually be whatever number of optically coupled tubes is required to produce the necessary quantum gain, which is on the order of 10^5 if the output is to be photographed. The various stages taken together should have a resolution sufficiently good that, despite demagnification, one can resolve about two line pairs per mm even at the edge of the chamber (i.e., points of light in the chamber 1/2 mm apart could be resolved).

Another essential feature of the second stage has already been mentioned, that it be easily gated. While it may not be necessary to gate the whole voltage of electrostatic tubes, at least, it is still quite difficult to raise the photocathode several kilovolts in 10^{-7} sec, and even a P15 phosphor loses 1/3 of its light in 10^{-7} sec. Thus it is very desirable that tube manufacturers supply gating grids to make really fast gating possible. Tubes with such grids do exist, and the RCA C-73435, for example, can easily be gated in 10^{-8} sec. Unfortunately, existing gating tubes have very little gain.

The output of the system is most simply a P11 phosphor optically coupled to a fast film, such as Royal-X Pan. However, an orthicon or any similar intermediate storage system is probably more desirable in every respect except cost. Even if one only photographs the kinescope output, one has greater control over the image conditions with such a storage system. However, the main advantage of a storage system is that the output can be put in digital form and recorded on tape. One of the chief features of the scintillation chamber is that it has potentially a much greater data-gathering power than any other visual technique, but much of this advantage is lost if the data must be processed through the intermediary of pictures, rather than going more directly into a computer. Direct tape readout from a normal orthicon is possible at the usual 1/30-sec rate, but video tape recorders are very expensive (around $50,000), and the resulting tape is not directly suitable for computers. Slow readout can be accomplished with the new G.E. orthicon, which has sufficiently good target storage, or by using an intermediate electrostatic storage tube, such as the excellent new Raytheon QK-685. The readout can be correlated with the position of fibers in a chamber to give a digital recording on computer tape of the position of lit fibers.

One might wonder whether the orthicon itself might constitute the second image intensifier in the system. It can be gated, and its flat photocathode face is an advantage. However, measurements made by Dr. H. S. Bridge and me indicate that even the most sensitive orthicon requires that about 10^4 photons be delivered to the photocathode to see a 1/2-mm light spot against a dark background. This is considerably better than the fastest film, but a lot of light amplification is still required ahead of the orthicon. It should be emphasized that for this use no increase in sensitivity can be achieved by the ability of the orthicon to integrate the input signal.

Intensifier orthicons have been discussed in a previous paper by Morton, and therefore only two comments will be made here. First, the asymptotic resolution of these tubes is of course poorer than for the image orthicons, but provided the demagnification in the system has not been large, the resolution at low light levels can be

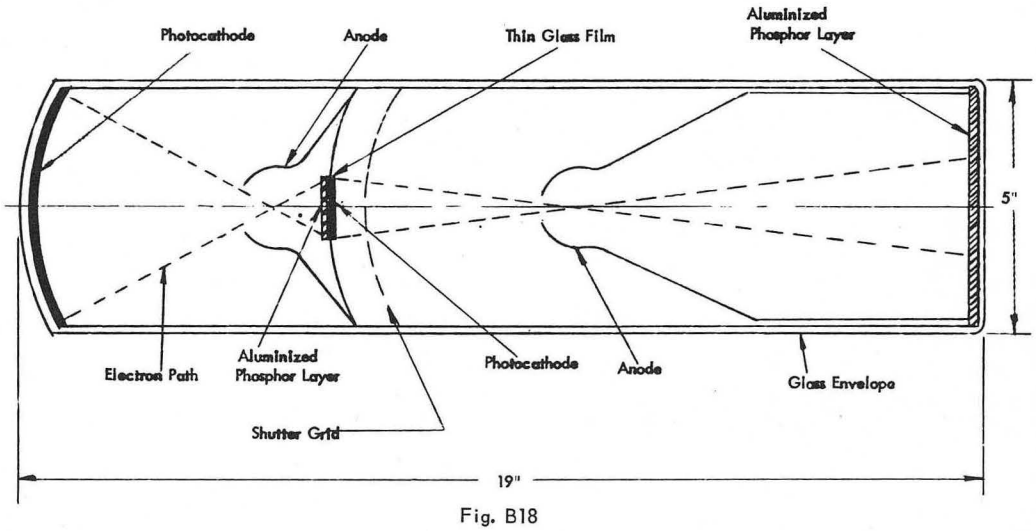

Fig. B18

adequate. Secondly, our measurements on a tube with a single intensifier stage indicate that about 200 photons must be delivered to the photocathode to see a 1/2-mm spot of light against a dark background. This means that the first intensifier stage in a system which uses 1/2-mm scintillating fibers and an intensifier orthicon need have only about three or four times as much gain as is required to overcome the optical coupling losses.

Recent improvements in orthicons and intensifier orthicons have been quite remarkable, but it is to be hoped that further improvements, such as using magnetic focusing on the intensifier section (to improve resolution and give a flat photocathode face), and perhaps employing the Isocon principle, will soon be forthcoming. The latter is a system in which the electrons in the beam returning from the orthicon target are at a minimum for dark areas, instead of at a maximum as in the normal orthicon, and hence the beam statistics are made better at low light levels.

At present, the intensifier section put on orthicons is a straight electrostatic system. Such electrostatic image intensifiers are made as separate tubes, and we shall discuss some of these now. Figure B18, which is the drawing of a tube now being constructed by Dumont, shows how electrostatic tubes work. Essentially there is a gain in light in going from photocathode to phosphor because of the kinetic energy given the electrons by the electrostatic field. The tube shown, which is about to be assembled, would make a suitable first element in a scintillation chamber system, since it will have a 5-in. fiber faceplate and a fast phosphor. It should be noted that Dumont has already made larger electrostatic tubes, but with only one stage of intensification. Such a tube, with a 16-in. photocathode, is shown in Fig. B19. While it is nice to know that big tubes can be built, this does not mean that one can have correspondingly large chambers, unless the optical-coupling problem is solved.

The only presently available electrostatic tube suitable for the front end of a scintillation chamber system of reasonable size is the Westinghouse WL-7257 shown in Fig. B20, which has one stage going from a 5-in. cathode to a 1-in. phosphor. With a P11 phosphor, tubes having quantum gains of about 100 have been made, and one tube has been built with a P15 phosphor. The resolution of the WL-7257 at the cathode is 3 lines/mm at the center and 2.2 at the edge, and the tube noise also seems suitable for the first stage.

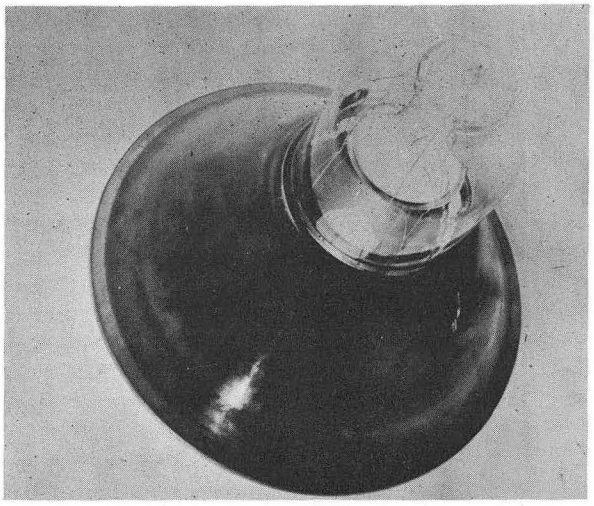

Fig. B19

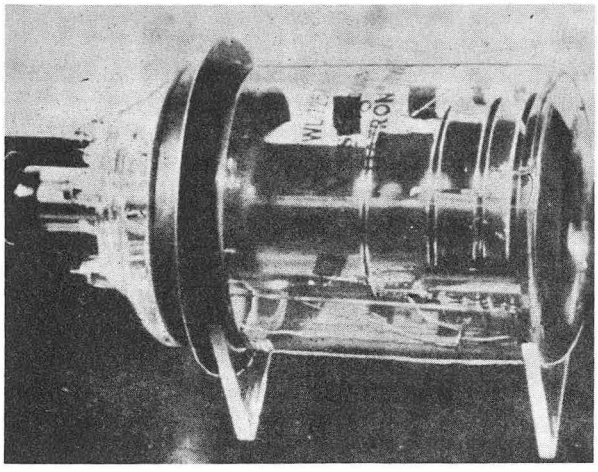

Fig. B20

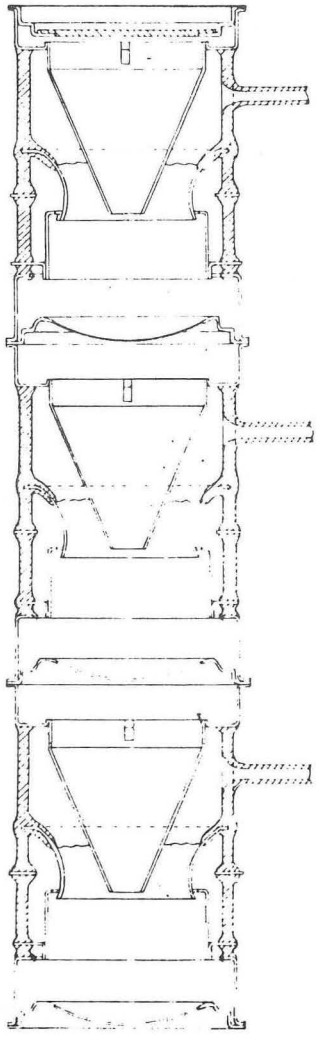

Fig. B21

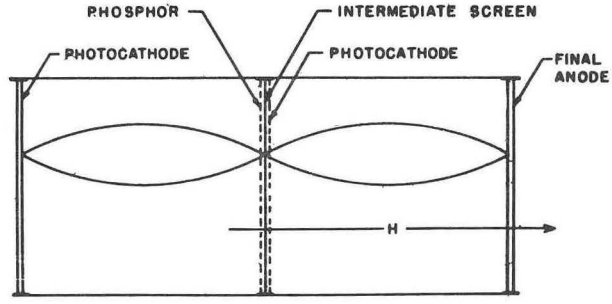

Fig. B22

As for an electrostatic tube for the second element in the system, the only one made at present (but not on a production basis) is a two-stage tube with a 1-in. photocathode. This tube, the RCA C-73458, has recently been improved remarkably by introducing multialkali cathodes, even in the phosphor-photocathode sandwich, and by better vacuum techniques, which have reduced tube noise considerably. With P11 phosphors these tubes now have gains of 10^3, but because of the small physical size of the tube the distortion is quite large and the edge resolution is typically 2 line pairs/mm, whereas it is 17 at the center. The central 1/2 in. of the tube could be used as the second element in a system having a 2-in. scintillation chamber of 1/2-mm fibers. Since a P15 first phosphor has been successfully put in the tube, it could even be used as a first element for a small chamber.

A three-stage version of this tube in a 4-in.-diameter envelope is being assembled by RCA and is shown in Fig. B21. This will have a 1-in. photocathode also, but the larger size of the tube should considerably overcome the distortion and make the resolution good enough for use with even a 5-in. chamber of 1/2-mm fibers.

The resolution of these tubes can be improved considerably by using magnetic focusing, as can be understood from Fig. B22, which is a drawing of a proposed Farnsworth (ITT) tube. In addition, the distortion of the magnetically focused tubes is considerably less than in electrostatic ones; and also, since a uniform electric field is used, the photocathode can be made flat, which simplifies the optical coupling problem. The magnetic tubes cannot be made to demagnify in any simple way, but this doesn't matter for the second element in the system and can be done optically for the first element, since the resolution can be sufficient. Present tubes suffer from the difficulty that the value of the magnetic field is very critical, but this trouble could be overcome if fields considerably stronger than the present few hun-

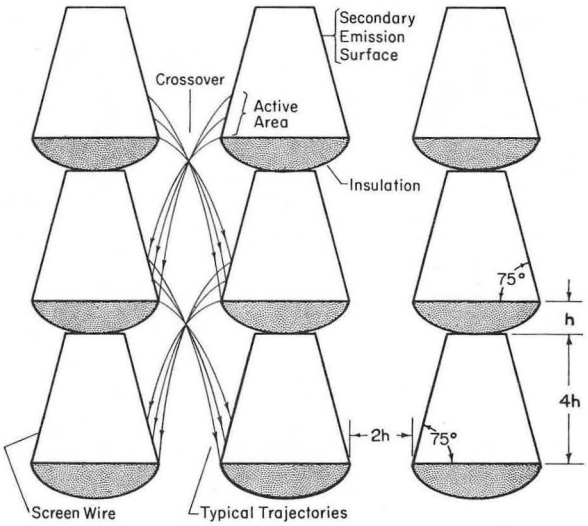

Fig. B23

dred gauss were used. The attempt to make tubes with very small fields results from military requirements on current and weight.

The main drawback of magnetic tubes is simply that no high-gain tubes have been made. Dumont has made some one-stage tubes in the past and is presently undertaking a two-stage one, for which the emphasis is on low noise and high resolution. RCA has a related program. Farnsworth (ITT) has also made some magnetic tubes for infrared use, and is now starting a program to make them with multialkali cathodes. Mullard regularly produces one-stage tubes with a gain of 10, and has made a few two-stage tubes, on which improvements now are being made. So far, however, no magnetic tubes are being designed specifically for scintillation chamber use, and the requirements of other users are unfortunately rather different.

A form of magnetic tube which was rather fully discussed in a previous paper by Anderson is that featuring transmission secondary emission, and it needs no further comment here.

The last type of tube to be discussed is the channeled image intensifier, and its operation can be understood from Fig. B23, which is a drawing of the dynode system of a tube being developed by the Chicago Midway Laboratories. Not shown in Fig. B23 are the necessary photocathode and field-shaping screen, which sends the photoelectrons into the various channels. Once into a channel, the photoelectron produces a cascade of secondaries, much as if it were in a "Venetian-blind" photomultiplier. Also omitted from the illustration are the accelerating section and the phosphor on which these electrons impinge.

In a tube of this type, one can of course continue to add stages to get any desired gain without losing contrast. The main problem is to make the channels small enough so as to get sufficient resolution. Chicago Midway makes the field-shaper screen and dynodes by an electroforming process, and has so far made them down to 50 mesh, and thinks they can go to 200 mesh. The insulation is provided by evaporating 0.003 to 0.005 in. of MgF_2 onto each sheet of dynodes, and tests indicate that this insulation will hold down to 200 mesh also. So far they have put together a 25-mesh, 7-stage tube, without photocathode or phosphor, and with voltages of 200 to 500 volts per stage, current amplifications equal to 3/4 of the secondary-emission ratios have been achieved, giving gains of 3 to 6 per stage. A similar 9-stage, 50-mesh tube has just been assembled, and they plan by the end of February to fabricate a 9-stage, 50-mesh tube complete with photocathode and phosphor. Information should then be available on possible problems of uniformity, background emission, spurious pulses, and ion and optical feedback.

There is also an evaluation program in progress at ITT to see if optical feedback in a channeled tube can be used to supply the necessary gain in one stage. Indications are that this will not work in a tube with good resolution.

If a channeled image intensifier were successful, it would make an excellent first element, since it can be very large and yet have a thin faceplate, as the photocathode is supported by the field-shaping screen. However, for very large units optical couplings would be out of the question, and hence it would be necessary to make the whole system in one envelope, including a fast phosphor backed by a photocathode. It would be desirable also to have electrostatic storage units at the end of the second set of channels for the readout.

While this ideal large tube is still probably a few years off, some of the others discussed are already at hand, and the two following papers will concern the actual observation of tracks in scintillators. This field is moving very rapidly now, and scintillation chambers will shortly be in use for doing experiments.

I should like to thank A. L. Bearman of Dumont, J. Burns of Chicago-Midway, G. Papp of ITT, R. G. Stoudenheimer of RCA, R. L. Stow of Westinghouse, and A. W. Woodhead of Mullard for supplying the latest information on their tube developments.

B-4. LUMINESCENT CHAMBERS

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Department of Physics
University of Michigan, Ann Arbor, Michigan

I would like to present a brief summary of luminescent-chamber work at Michigan by Professor Martin Perl and me. As Professors Caldwell and Reynolds have already outlined the general nature of the problems involved and the characteristics of available image tubes, I will proceed directly to a description of our first successful image-tube system. Figure B24 is a schematic sketch and Figs. B25 and B26 are photographs of the apparatus, which is seen to consist of a small sodium iodide crystal (1-1/2 inches in diameter, 3/4 inch thick), two RCA C-73458 (two-stage) image tubes, and a a Westinghouse WX-3897 (one-stage) image tube, coupled by appropriate lenses.

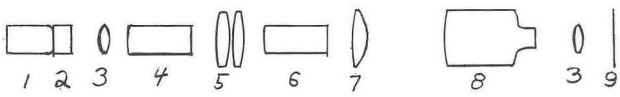


Fig. B24. Schematic diagram of cascade geometry.
1. 6292 Photomultiplier.
2. 1-1/2-inch-diameter x 3/4-inch-thick thallium-activated sodium iodide crystal.
3. Erfle wide-angle eyepiece lens, 1-1/2 inches, E.F.L.
4. Two-stage image tube, R.C.A. C-73458A #25-PI 260.
5. American Optical Company special eyepiece lenses.
6. Two-stage image tube, R.C.A. C-73458 # 22-PI 300.
7. f/0.75 110-mm Kodak Fluro-Ektar lens corrected to 10:1 magnification.
8. One-stage image tube, Westinghouse WX 3897 #841006.
9. Photographic film, Eastman Kodak Royal-X Pan.

We have thus far been inclined toward what might be called the "homogeneous" chamber, consisting of a single scintillator crystal, in contrast to the filamentary chamber as discussed by Caldwell and Reynolds. This allows much simpler optical coupling to the image tube than in the filamentary chamber, and we believe that inorganic scintillator chambers of experimentally useful size are feasible.

The gain of the system is 2 to 8×10^4 photons on the film per photon on the photocathode of the first image tube. The second image tube is gated upon arrival of a pulse from the photo-

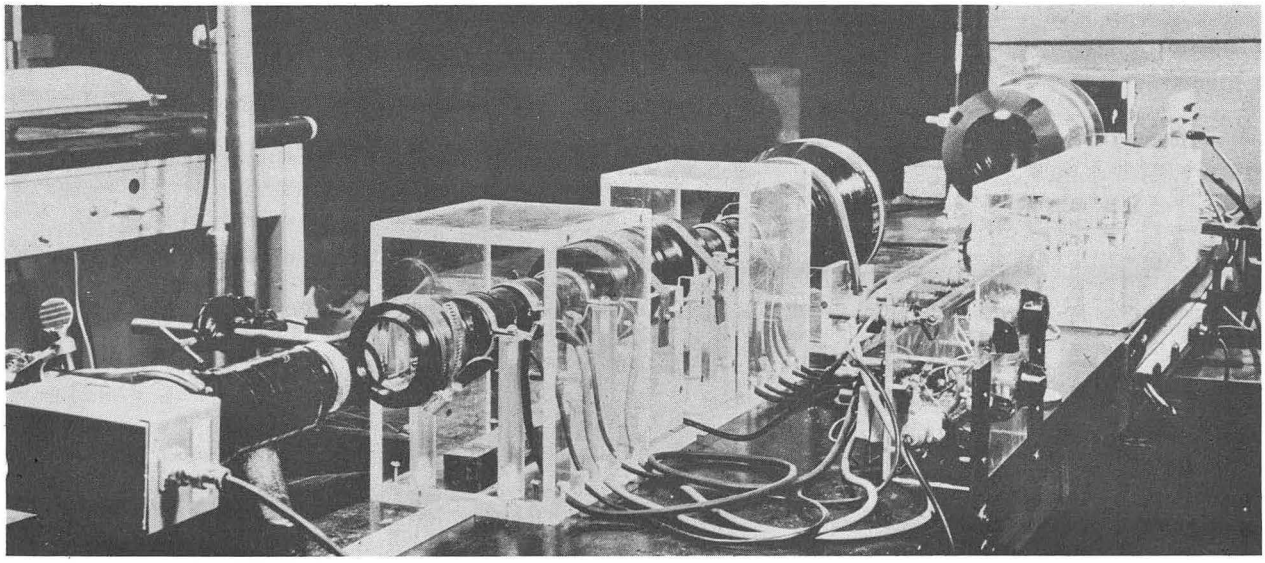


Fig. B25

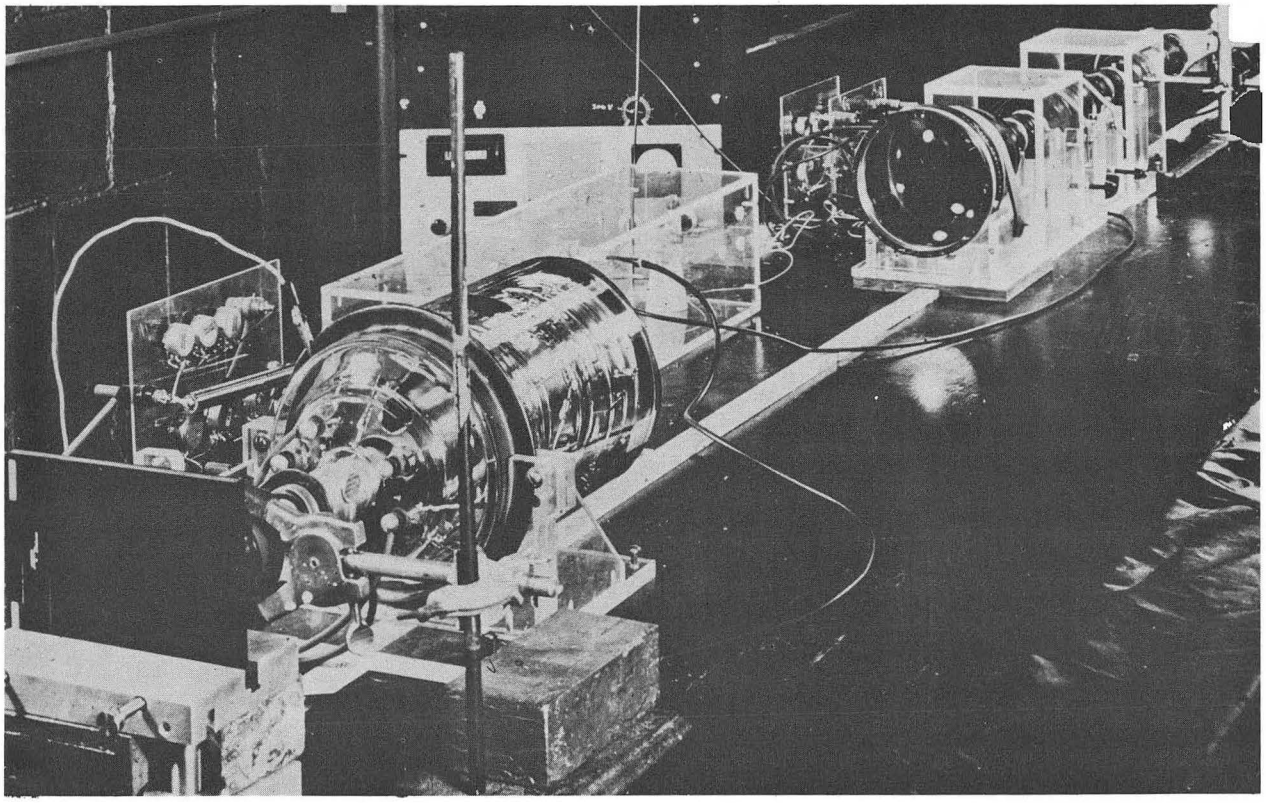


Fig. B26

multiplier by removing a positive cutoff bias on the photocathode for a gate interval of the order of a millisecond. The image tubes employ P11 and P20 phosphors, so that even with this long gate interval considerable light is lost because of the long decay component of the phosphor.

Figure B27 is a reproduction of cosmic-ray tracks photographed with this arrangement, using Royal-X Pan film. Several hundred cosmic rays were photographed with this system in mid-December of last year.

Subsequently we added another WX-3897 coupled to the other Westinghouse tube with a second f/.75 lens, giving us another order-of-magnitude gain. In Fig. B28 are cosmic-ray

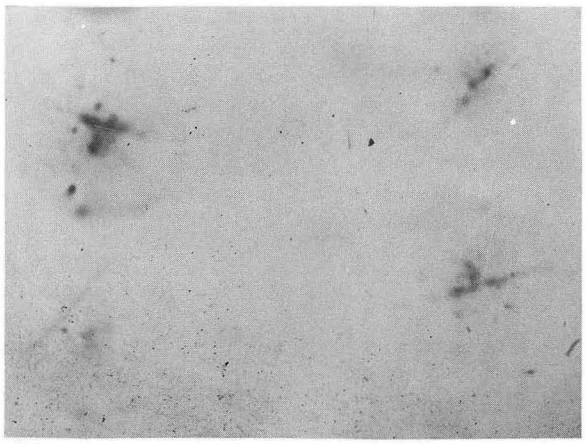


Fig. B27

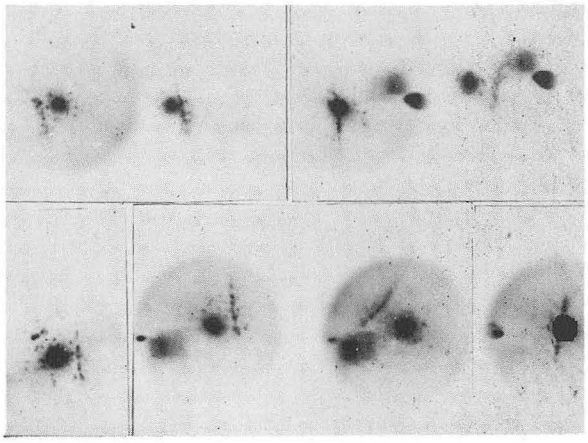


Fig. B28

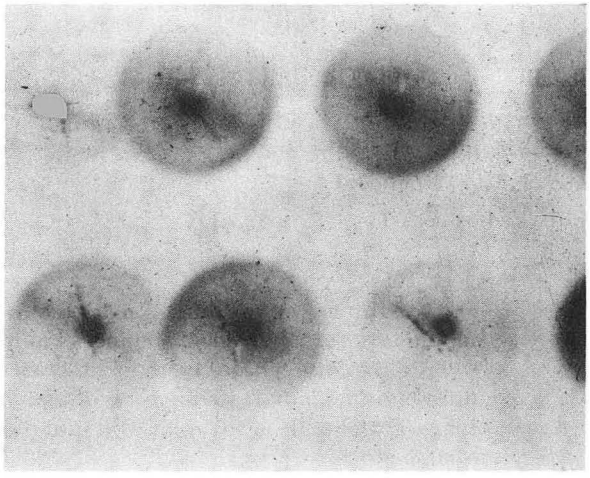


Fig. B29

tracks photographed with this four-tube system. In several instances it is possible to see that the track is composed of single dots: these correspond to single photoelectrons from the first photocathode. From the geometry and the estimated scintillator and cathode efficiencies, the track images should contain 50 to 100 photoelectrons, which is in qualitative agreement with the photographs. The spot in the center of each frame was due to faulty gating and has since been eliminated. Figure B29 contains more cosmic-ray tracks, here with the lens aperture made small to increase the track resolution (depth of field).

Most of the photographs are seen to contain a few brighter dots corresponding to electrons released upon positive-ion bombardment of the first cathode. The number of these is in proportion to the gate length, so that we believe they will be no problem with 1-microsecond gating such as will be used in experiments.

Figure B30 contains tracks photographed in a sodium iodide crystal 3 in. in diameter and 2-1/2 in. thick. The most severe limitation on the utility of the present system is its resolution. This is currently due to the use of low-quality lenses as much as to the image tubes themselves, and is a more severe limitation than the resolution limit imposed by the finite optical depth of field in the scintillator.

Some of our image tubes are limited in their

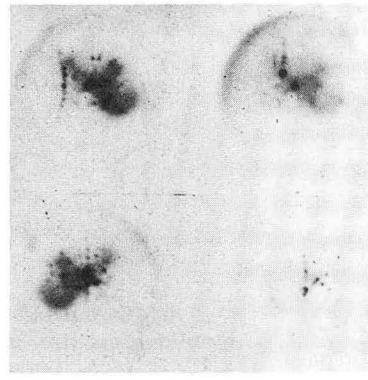


Fig. B30

utility by "noise," that is, screen brightness due to positive-ion bombardment of the cathode. Tubes also occasionally contain "hot spots" of some sort which give rise to intermittent bright flares on the output screen, as seen in the photographs of Fig. B28.

In conclusion, I should like to emphasize our belief that it is practical to consider luminescent-

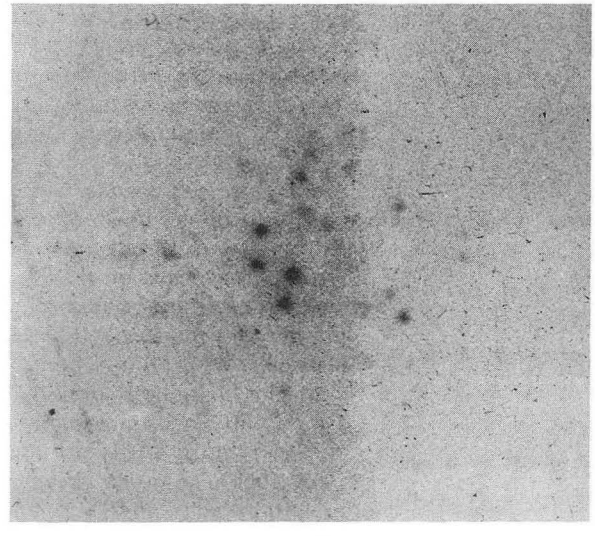


Fig. B31

chamber experiments in high-energy physics this year, using existing image tubes, available optical components, and homogeneous or filamentary scintillators several inches square.

(Note added subsequently) Figure B31 is a photograph of single quanta from an incandes-

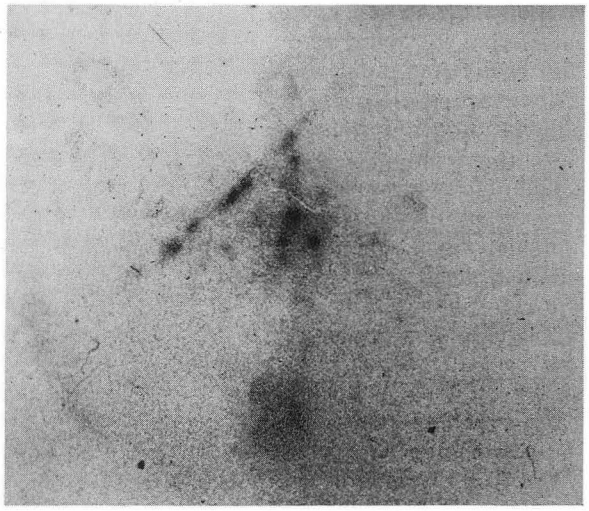


Fig. B32

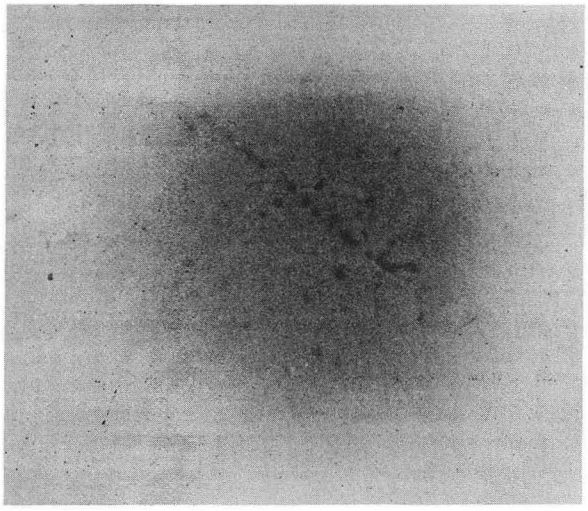


Fig. B33

cent light bulb together with a few ion spots. Figures B32 and B33 contain more tracks photographed in the 3-in. sodium iodide crystal, using better optical components. These were taken with various combinations of the RCA and Westinghouse tubes described above.

B-5. COSMIC-RAY TRACKS IN FILAMENT SCINTILLATION CHAMBERS

George T. Reynolds, R. Giacconi, and D. Scarl

Palmer Physical Laboratory
Princeton University, Princeton, New Jersey

Presented by George T. Reynolds

We have conducted an extensive program of image-tube study to determine the operating characteristics of several Westinghouse WL-7257 and RCA C-73458 (two-stage) tubes with P11 and P15 phosphors. Experiments have shown that microsecond pulsing of the tubes with short-persistence phosphors is feasible although it appears that the gain decreases somewhat under these conditions. There is evidence that the P15 phosphors have decay times somewhat longer than the 1 μsec sometimes reported, and also that the P11 can be as short as 40 or 50 μsec at low light levels. This latter effect may be due in part to a quenching effect incurred in processing. By use of a calibrated photomultiplier, background light from the image tubes has been measured as a function of voltage. Tube backgrounds of $\sim 10^{-5}$ watt/cm^2 are considered good; backgrounds of $\sim 10^{-2}$ μwatt/cm^2 are very bad.

By selecting some of our best tubes we arranged the cascade shown in Fig. B34. Here T1 is a Westinghouse WX-4047 P15 phosphor. This tube has a demagnification of 5:1 and a quantum gain at the voltage used (23 kv) of about 11. The T2, T3, and T4 are RCA two-stage tubes run at 16 kv with gains of 290, 930, and 125 respectively. The lenses have transmission on the order of 10%, except for the camera lens, which has 3% transmission. The film used was Royal-X Pan. Thus the over-all intensity gain of the system to the film was 3.5×10^5. Several filament chambers were used. In each case the filaments were put in direct contact with the window of the Westinghouse tube. Since this window was thick (0.25 in.), the resolution was very poor. In some runs the chamber shown in Fig. B35 was used. It is 4 in. high, 1 in. wide, and 1-1/2 in. deep. In other runs, a chamber 1 in. in diameter by 1-1/2 in. deep was used.

Microsecond pulsing of the second stage was not used, but the last stage was pulsed on for 1 msec. The pulse signal was supplied in some runs by the coincidence arrangement S1—S2 shown in the figures, and in some runs by a photomultiplier viewing the filament chamber on the face opposite to the image tube. In general we found it much more difficult to photograph

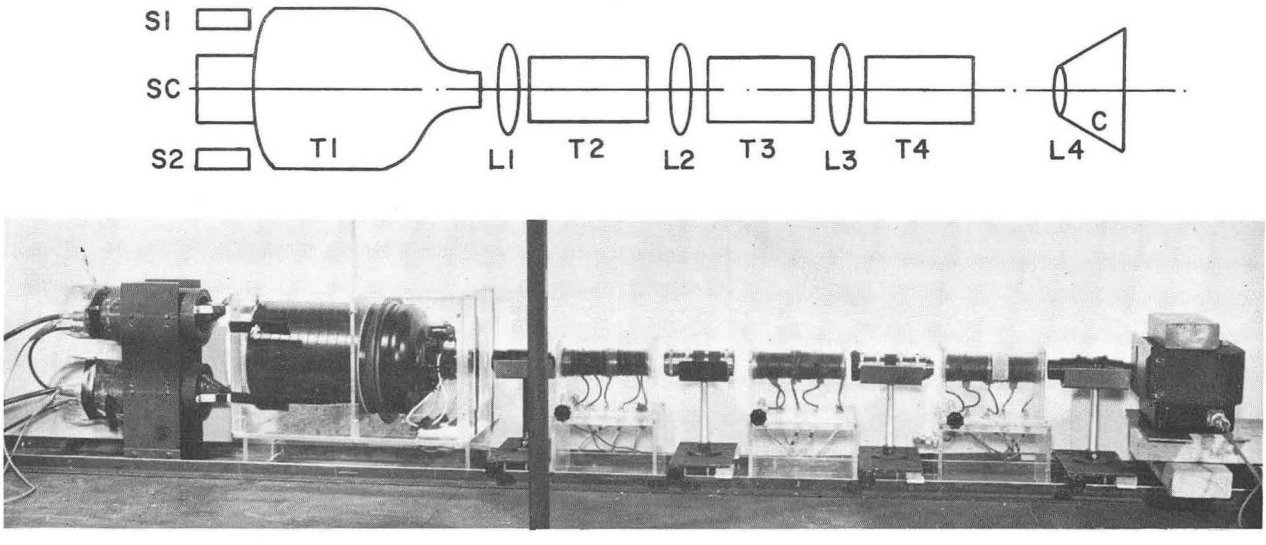


Fig. B34

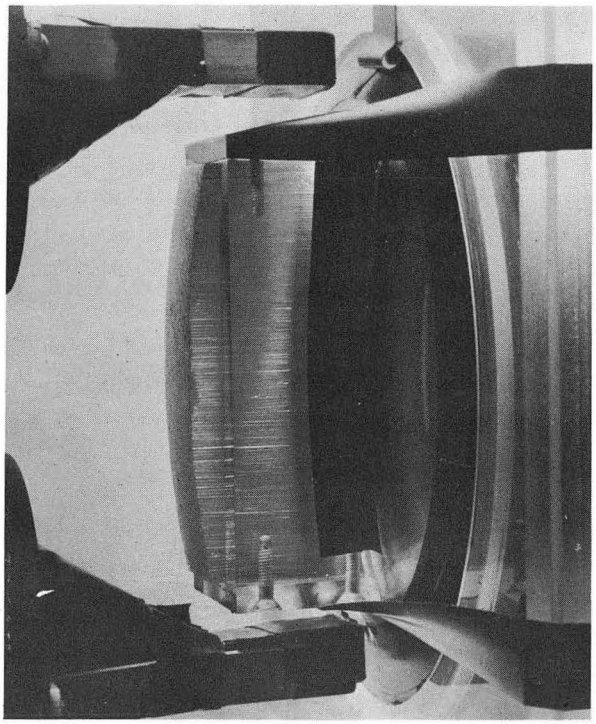


Fig. B35

tracks when the coincidence circuit was used. This leads us to suspect that some of the tracks recorded with the photomultiplier triggering are not minimum-ionizing. Examples of tracks in the coincident counter case are shown in Fig. B36 (4-in. chamber) and Fig. B37 (1-in. chamber). Figures B38 and B39 are of tracks obtained by using the photomultiplier triggering. Figure B40 is an enlargement of Fig. B39.

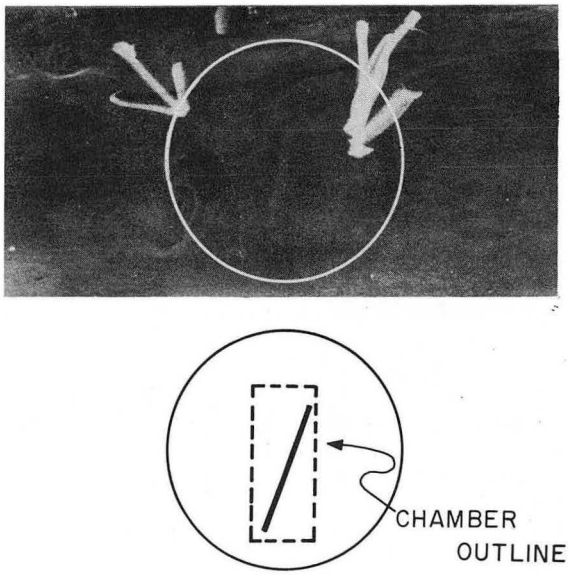


Fig. B36a

Fig. B36b

Discussion

Roberts: Professor Caldwell gave us a very good summary of the philosophy of the development of the image intensifier systems as it has gone up to now. There's one point on which perhaps there is some divergence of opinion, and it might be worth pointing it out. That was his belief that the image orthicon is preferable to the straight cascade image intensifier and photographic-film technique for recording the final image. I think this is at the moment a matter of opinion, and we will have to have more experience with both of these till we find out which is true. I think it's certainly true that the orthicon will be more expensive, and in fact I don't know any other group except the MIT group or perhaps the Berkeley group which could even afford to try it.

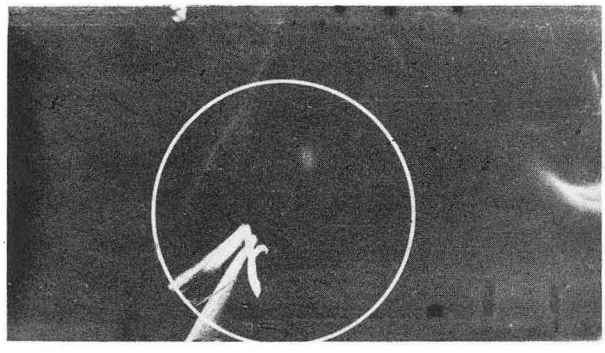
Also, I'm not convinced that the output of the orthicon is "digitized"--I think this is stretching the term. It doesn't come out any faster, certainly, than the photographic film. It takes 1/30 second with conventional techniques to get one frame, and a film can do faster than that. Of course, so can the orthicon if you speed it up.

I want also to congratulate Professors Jones and Perl and Professor Reynolds on their achievements. There's one thing Professor Jones said, however, which I think has to be taken with a bit of caution. He mentioned that he thinks that the system is ready for people to start duplicating and to start doing experiments this year. I think Professor Jones is ready to do it, but if

everybody else tries to do it, nobody will be able to. The tubes that have been described are, for the most part, available only in limited quantities. The Westinghouse tube is being made in a factory in Elmira by production people; but the RCA two-stage tubes are still being made in a pilot shop by hand, one at a time, by engineers. And these engineers are needed to do the research and development on the three-stage tubes that Professor Jones is so anxiously waiting for. So if there's going to be any large demand for two-stage tubes --and I'm not trying to scare anybody from buying them--let us know so that we can try to get them into a production shop. If we get this tube into the production shop at Lancaster, everybody can have them. But let's not tie up Mr. Stoutenheimer. He's got his hands full, and he's nearly been fired already for doing so much for us!

Wiegand: I think those were quite pertinent comments, and I would agree as I see this array of lenses and things. It's a wonder that we can see anything.

A remark was made about the little blobs that appeared so nicely on the track. They represent some kind of feedback amplification, and I think there is even a group working on applying this as something to make the tracks more visible rather than nuisances.



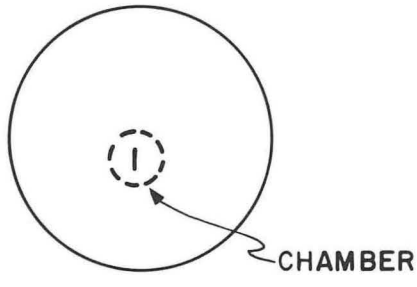
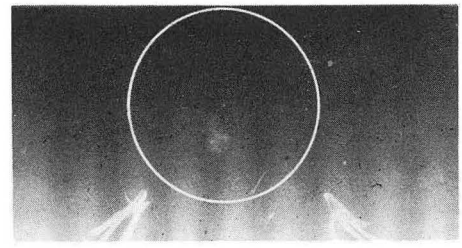


Fig. B37



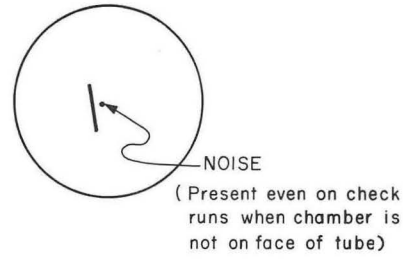
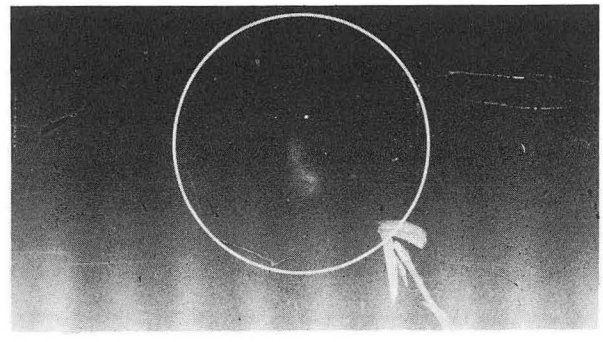


Fig. B38



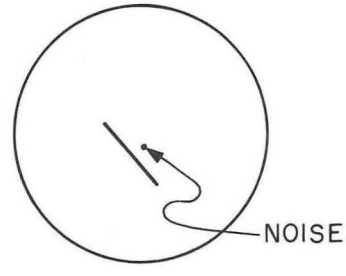


Fig. B39

Fig. B40

B-6. TIME SORTING OF MILLIMICROSECOND PULSES

C. Cottini, E. Gatti,* V. Svelto, and F. Vaghi
Laboratori C. I. S. E., Milano, Italy
Presented by Emilio Gatti

We will deal with a time sorting of millimicrosecond pulses, based on a vernier technique, which we have been developing since 1955, [1,2,3] and which has led to several successively improved instruments and to a theoretical analysis of resolving time of scintillation-counter pulses.[4] Other instruments have been developed according to our suggestions,[5] and another with some different features has been independently developed.[6]

The most recent version of our instrument is shown in the block diagram, Fig. B41. The pulses of the photomultipliers excite two resonant circuits (20 MHz and 20.2 MHz): the resulting wave trains are mixed in a diode bridge modulator; the phase of the low-frequency modulation product is measured with respect to the arrival time of a quasi-coincident couple of pulses ($2x10^{-8}$ sec). This phase measurement is accomplished through a time-to-height converter based on a ramp function started by the $2x10^{-8}$ -sec coincidence and stopped by the first zero crossing of the modulation product.

It should be noted that the definition of the time of occurrence of a pulse by means of the excitation of a high-Q resonant circuit dispenses with the use of millimicrosecond circuit techniques because we pick up with the resonant circuit a definite Fourier component of the input pulse which—apart from a constant attenuation and constant phase shift—is unaffected by any transfer function. The resonant circuits are excited linearly to prevent a systematic error in time measurement related to the amplitude of the input pulses.

At high counting rates, the resonant circuits should be protected against successive pulses after an excitation; this is provided, for 4 μsec, by a reversal of voltage of two successive dynodes of the photomultipliers, driven by the slow coincidence (Fig. B42). The slow coincidence supplies also a signal to remove, for 4 μsec, the damping that normally protects the resonant circuits from excitation due to single pulses in both channels. We obtain a calibration stability better than $5x10^{-11}$ sec for a day with a feedback arrangement: a pair of artificial coincident pulses is sent to the two photomultiplier anodes every 0.1 sec, and the resulting pulse at the output of the instrument is compared by a reference amplitude discriminator. This corrects continuously through a large time constant the reverse voltage of a junction diode, which acts as a controlled capacitor in parallel to one of the resonant circuits.

Amplitude requirements on photomultiplier pulses can be introduced, and they control the output gate of the instrument.

Figure B43 shows the resonant circuits with damping devices and feedback arrangements for compensating losses. For satisfactory operation of the mixer, it is necessary to have the wave trains of standard amplitude. The wave trains have to be limited without introducing amplitude-dependent phase shifts. We have two limiters made by vacuum diodes 6AL5, in parallel with the resonant circuits of the amplifying stages and a 6BN6; the 6BN6 alone is not sufficient because the grid voltage modulates the velocity of electrons in flight. The tuning adjustment of the low-Q stages provides an easy way to control the dependence of phase on amplitude; this function reverses its behavior passing though the resonance.

The scheme of the time-to-height converter is shown in Fig. B44; the design follows some circuits of Chase and Higinbotham[5] and Lepri and others.[7] Figure B45 shows a prompt-coincidence curve for a Co^{60} gamma source. The am-

* Politecnico di Milano e Laboratori C.I.S.E.

[1] C. Cottini, E. Gatti, and G. Giannelli, Nuovo cimento 4, 156 (1956).

[2] C. Cottini and E. Gatti, Nuovo cimento 4, 1550 (1956).

[3] C. Cottini and E. Gatti, Nuclear Instr. 2, 88 (1958).

[4] S. Colombo, E. Gatti, and M. Pignanelli, Nuovo cimento 5, 1739 (1957).

[5] R. L. Chase and W. A. Higinbotham, Rev. Sci. Instr. 28, 448 (1957).

[6] H. W. Lefevre and J.T. Russel, Bull. Am. Phys. Soc. 2, 175 (1957).

[7] F. Lepri, L. Mezzetti, and G. Stoppini, Rev. Sci. Instr. 26, 936 (1955).

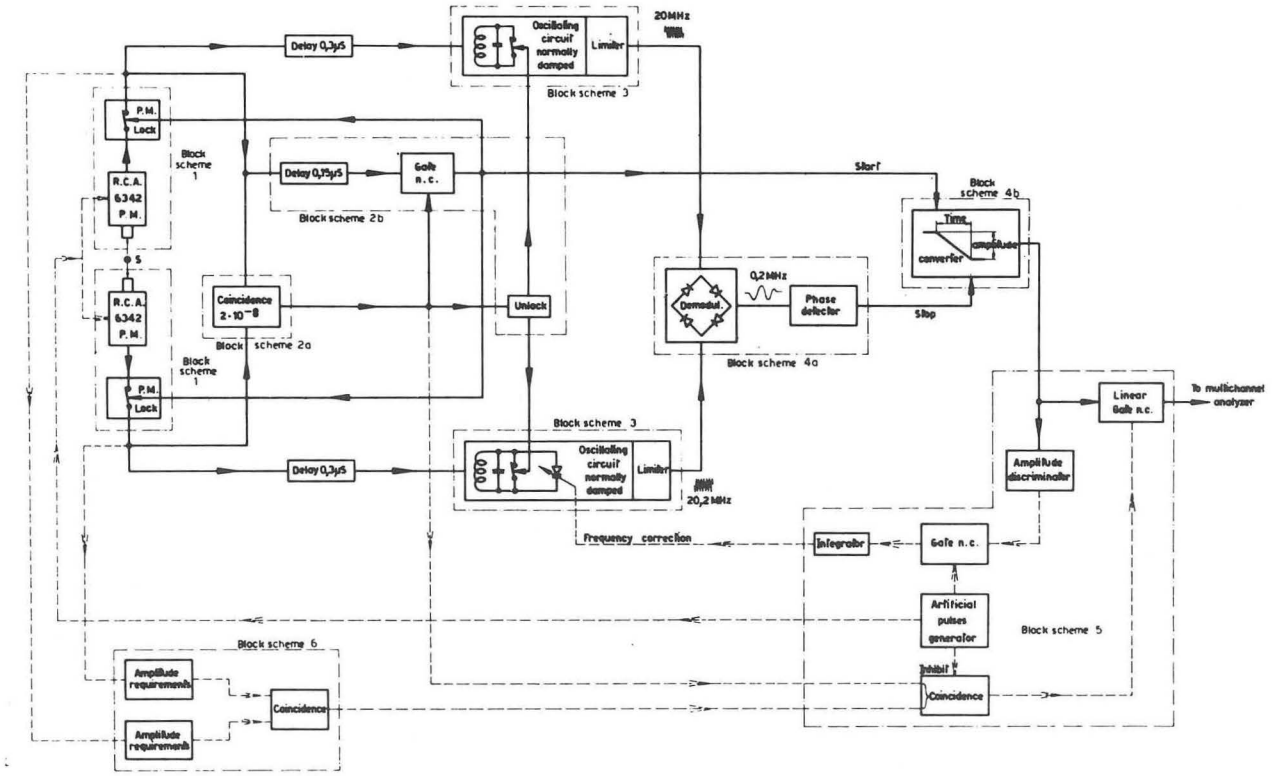


Fig. B41. Block diagram of time sorter for millimicrosecond pulses.

plitude requirements accept only the upper part of the 1.3-Mev gamma rays.

Figure B46 shows a measure of positron lifetime in Teflon. A source of about 15 μC of Na^{22} is sandwiched in the Teflon and placed between the photomultipliers. One of the photomultipliers accepts only the upper part of the 1.28-Mev gamma rays and the other accepts only the upper part of the 0.51-Mev annihilation quanta.

Figures B47 and B48 show measurements of positron lifetime in Al and Fe respectively. In Figs. B47 and B48 the prompt-coincidence curve is obtained by replacing the Na^{22} source with a Co^{60} source without changing the amplitude requirements in both channels.*

* We thank Prof. Germagnoli, who is collaborating with one of the authors, for the data of Figs. B46, B47, and B48, which are preliminary results of a set of experiments on positronium decay in different materials.

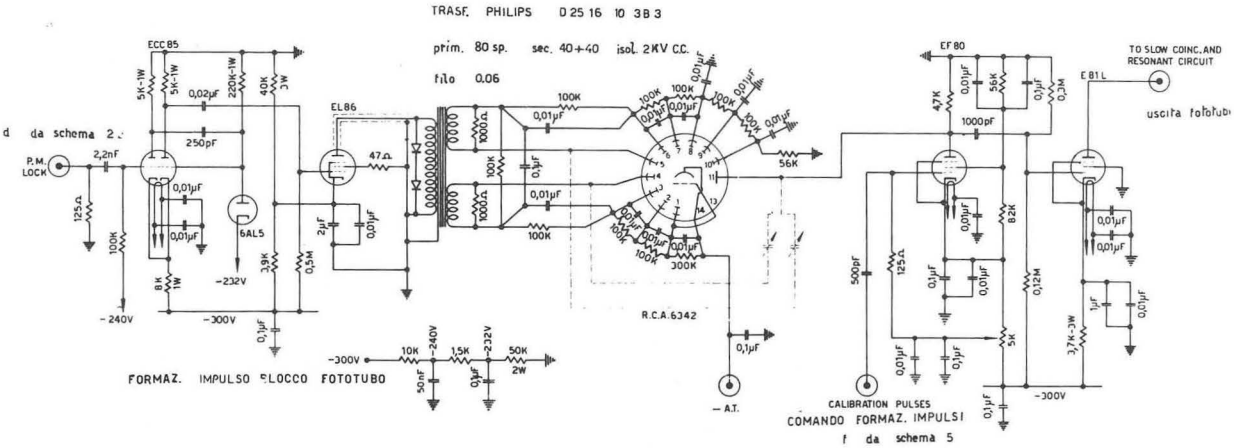


Fig. B42. Electronics associated with photomultiplier tube.

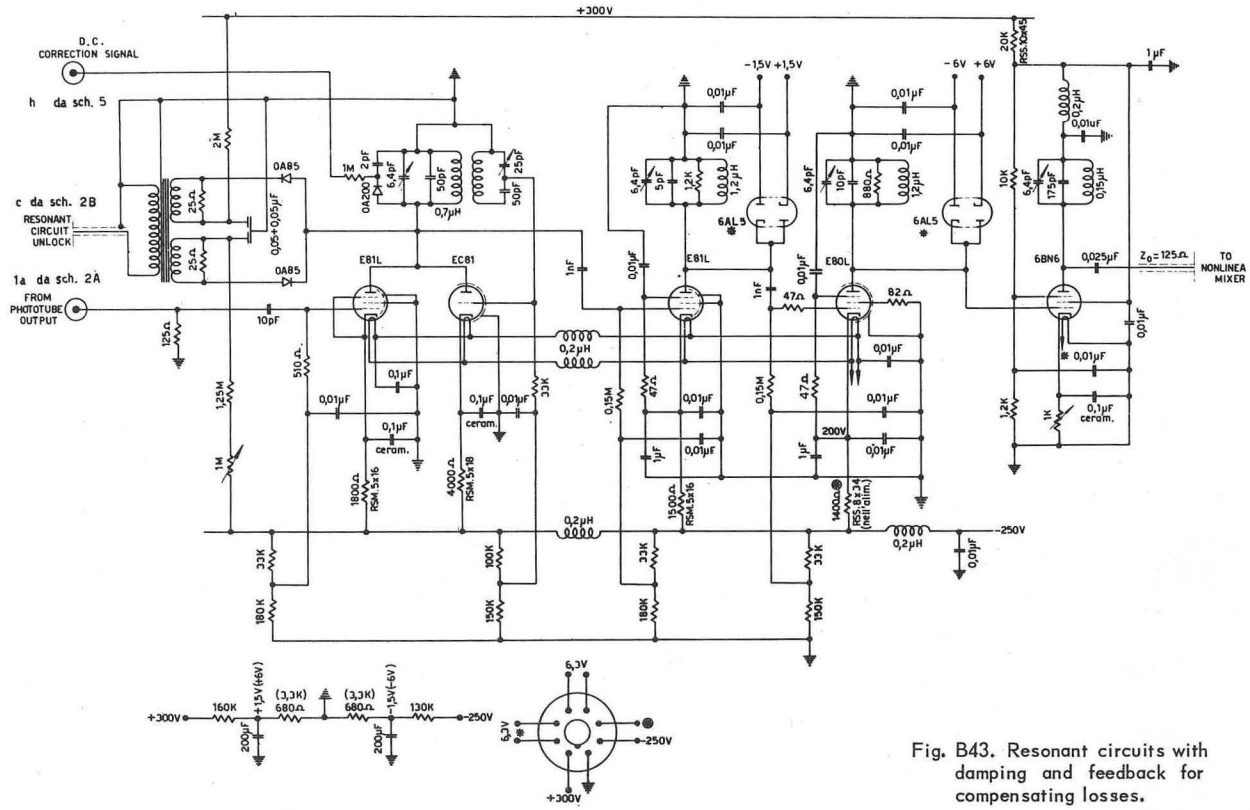


Fig. B43. Resonant circuits with damping and feedback for compensating losses.

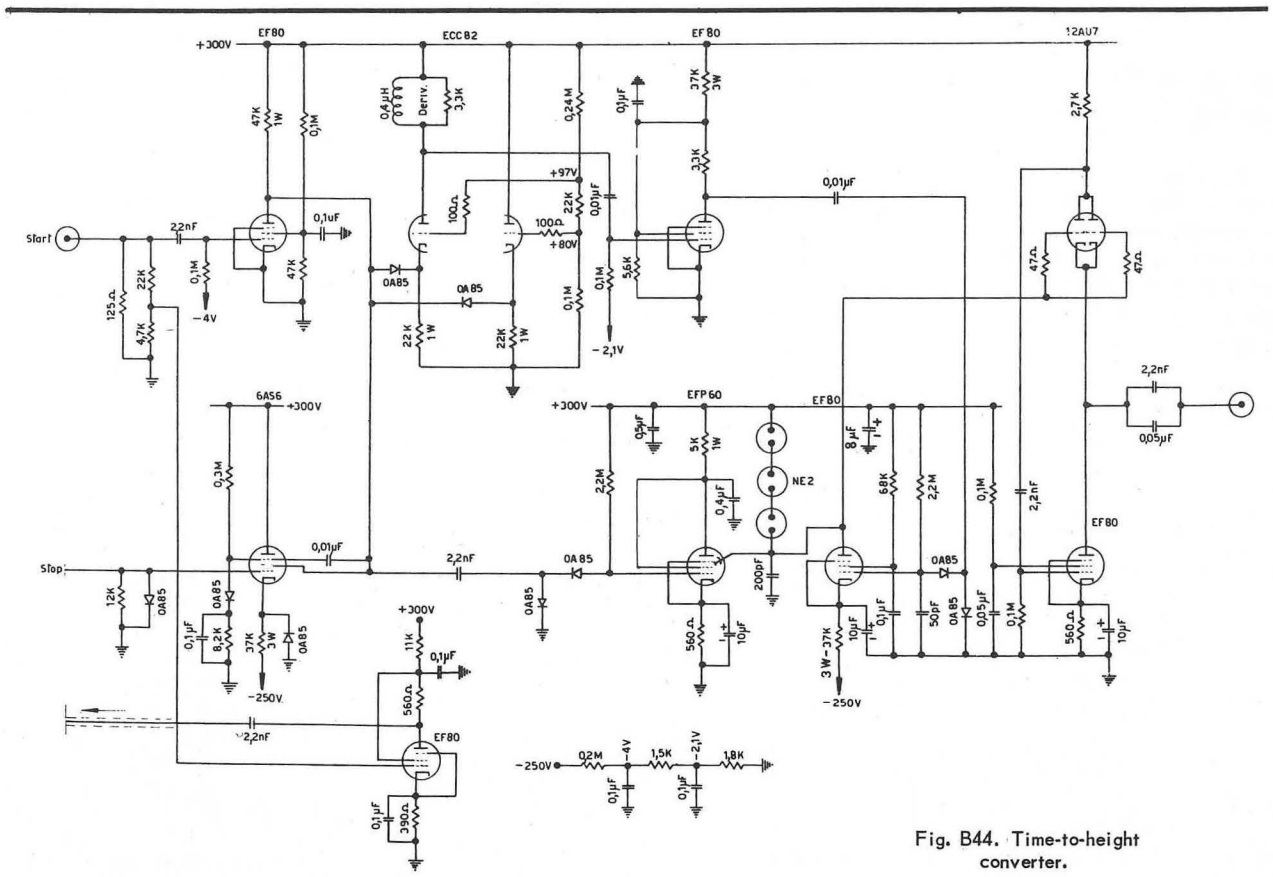


Fig. B44. Time-to-height converter.

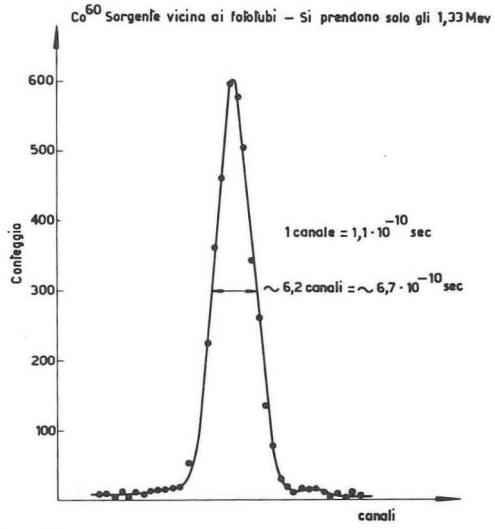


Fig. B45. Prompt-coincidence curve for gamma rays from a Co^{60} source. (Co^{60} source near the phototube--only 0.51-Mev gamma photons accepted.)

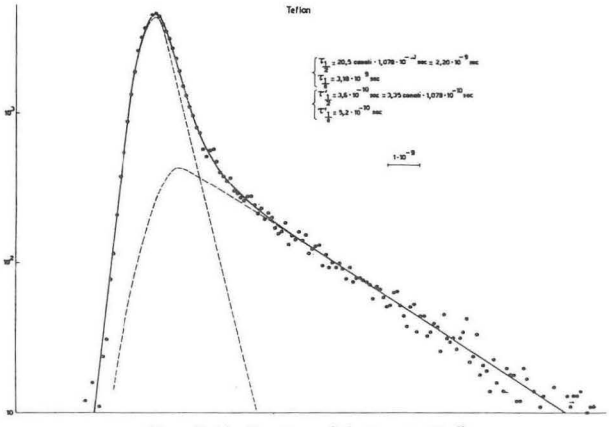


Fig. B46. Positron lifetime in Teflon.

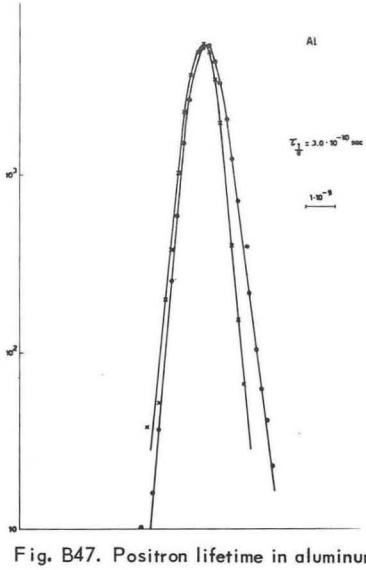


Fig. B47. Positron lifetime in aluminum.

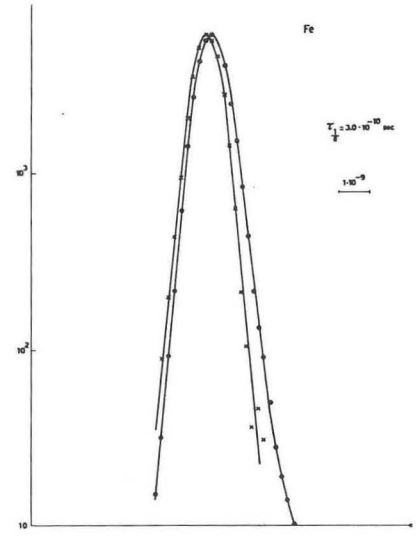
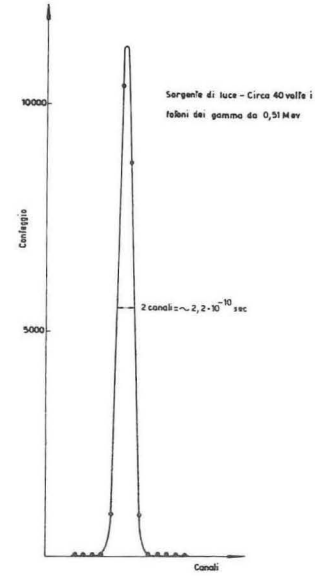


Fig. B48. Positron lifetime in iron.

Fig. B49. Coincidence curve for artificial light pulses. (Light source about 40 times the light pulses due to 0.51-Mev γ rays.)



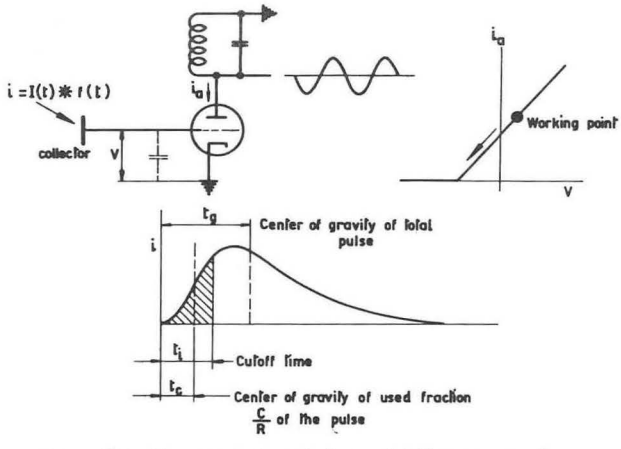


Fig. B50. Characteristics of photomultiplier output pulses.

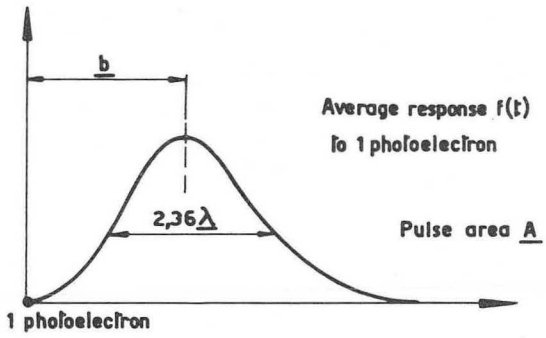
Figure B49 shows a curve obtained with artifical light pulses of an amplitude corresponding to 40 times the light pulses due to 0.51-Mev gamma rays with a plastic scintillator. The artificial light source is a hydrogen flash tube as described by J. H. Malmberg.[8]

The ballistic excitation of the resonant circuits is not the only possible method of using such an instrument as the one described. Although this method was the only one tested, a complete theoretical investigation has been developed of the accuracy obtainable with various suggested methods of extracting time information from the output pulse of a photomultiplier.

Four methods have been investigated, for which the time of the event is variously defined (see Fig. B50) as:

A. The center of gravity of that part of the current pulse which corresponds to the collection of a definite fraction $\frac{C}{R}$ of the total average charge R;

[8] J. H. Malmberg, Rev. Sci. Instr. 28, 1027 (1957).



Variance of center of gravity b

$$\varepsilon_b^2 = \varepsilon_{cd}^2 + \frac{\varepsilon_{dd}^2}{g-1}\left(1+\frac{2}{g}\right)$$

Pulse width $\lambda^2 = (n-1)\varepsilon_{dd}^2$

Relative variance of pulse width λ

$$\varepsilon_\lambda^2 = \frac{1}{(n-1)^2(g-1)}\left(1+\frac{3}{2g}\right)$$

Relative variance of gain A

$$\varepsilon_A^2 = \frac{1}{g-1}$$

Fig. B51. Parameters of the phototube.

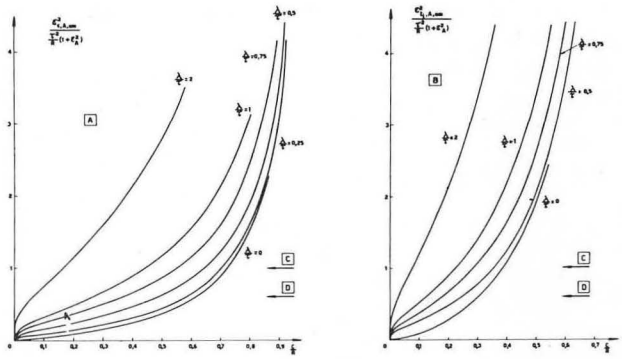


Fig. B52

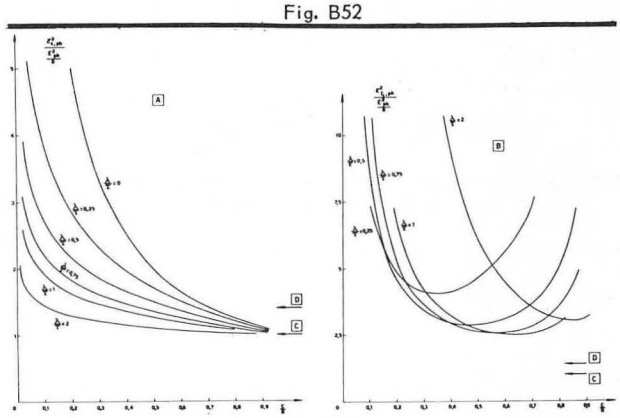


Fig. B53

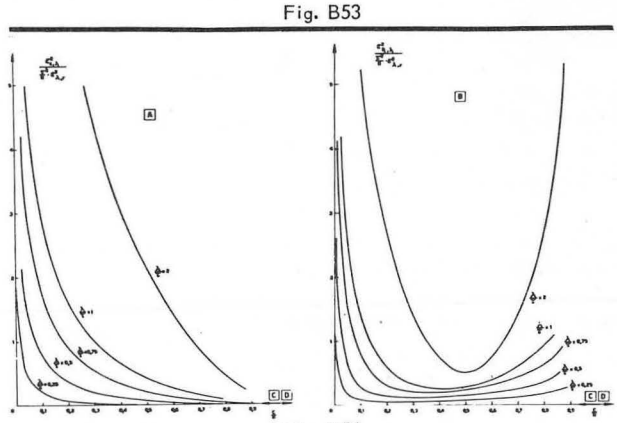


Fig. B54

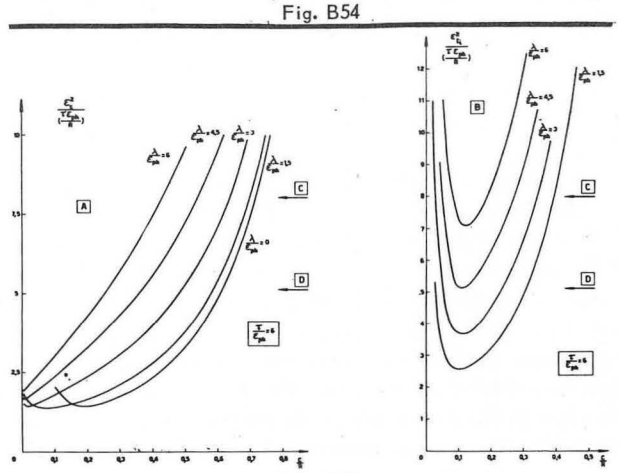


Fig. B55

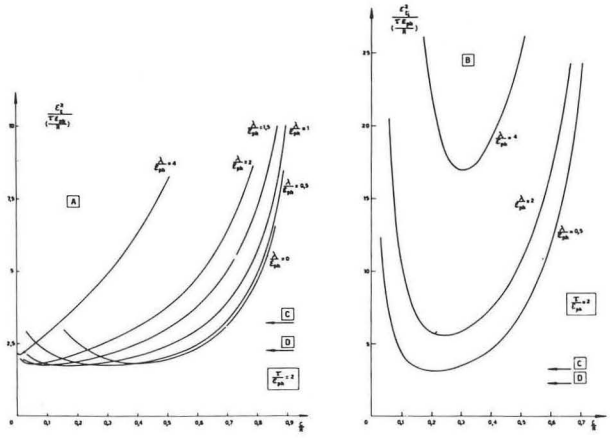


Fig. B56

B. The instant at which a definite fraction $\frac{C}{R}$ of the total average charge R has been collected;

C. The center of gravity of the total current pulse;

D. The phase of a resonant circuit excited linearly by the total current pulse having a period $T = \frac{2\pi}{\omega}$ comparable to the total pulse width τ ($\omega\tau = 1$).

For the sake of analysis the phototube has been characterized by the following parameters (see Fig. 51):

E_A^2 = relative variance of the phototube gain;

E_{ph}^2 = variance of the time interval between the emission of one photoelectron and the center of gravity of the consequent current output pulse f(t);

λ^2 = the second moment of f(t) referred to its center of gravity; λ is called the width of f(t);

$E_{\lambda r}^2$ = relative variance of λ.

Further, an exponential law for the scintillation light,

$$I(t) = \frac{R}{\tau} \quad \exp(-t/\tau),$$

has been considered. I(t) is normalized so that R represents the average number of photoelectrons emitted in one scintillation.

Contribution to total variance due to

(a) Poisson statistics in emission of photoelectrons and variance of phototube gain E_A^2 and of yield of the photocathode;

(b) variance of the center of gravity of one photoelectron pulse E_{ph}^2 ; and

(c) variances in pulse width on one photoelectron pulse $E_{\lambda_2}^2$

have been separately evaluated and are compared for the four cases A, B, C, and D of use of the output pulse (Figs. B52-54).*

And finally in Figs. B55 and B56 these variances are summed with the proper weights for two typical numerical cases; that is:

$$\frac{\tau}{E_{ph}} = 6, \text{ for instance } \begin{cases} \tau = 3\cdot 10^{-9} \\ E_{ph} = 5\cdot 10^{-10} \end{cases}$$

and

$$\frac{\tau}{E_{ph}} = 2, \text{ for instance } \begin{cases} \tau = 10^{-9} \\ E_{ph} = 5\cdot 10^{-10} \end{cases}$$

Both the nonlinear methods show a resolution that has a minimum for a definite $\frac{C}{R}$; however, this minimum is much more flat for Method A, and further, this minimum is lower.

The value of the minimum is quite insensitive to the pulse width λ for Case A, while Method B is very highly sensitive to λ.

Linear methods C and D give variances larger than nonlinear methods A and B for large $\frac{\tau}{E_{ph}}$ (for instance, $\frac{\tau}{E_{ph}} = 6$); they are nearly equivalent in the case $\frac{\tau}{E_{ph}} = 2$, and they are greater for lower values of this parameter (as happens, for example, with Čerenkov counters). Linear methods, however, have the advantage of no systematic dependence of time (as "felt" by the instrument) on pulse amplitude.

Method B shows greater sensitivity than Method A to pulse amplitude. This theory was partially developed in a previous paper,[4] and the further developments which led to the results shown here will be published extensively in the near future.

* We thank the "Centro Calcoli Numerica" of the Politecnico di Milano, which carried out the numerical calculations with a digital electronic computer.

C-1. A TIME-DELAY—TO—AMPLITUDE CONVERTER

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National Bureau of Standards, Washington, D. C.
Presented by Zoltan Bay

Introduction

The conversion of time delay to amplitude together with the use of a multichannel pulse-height sorter turns a coincidence circuit into a multichannel coincidence system. The theoretical advantages of such a system are discussed below. In the experimental part of this paper a circuit is described which performs the pulse-height limiting of the input pulses by means of a grid-controlled secondary-electron emitter tube. To measure the time overlap between shaped pulses, a diode bridge coincidence circuit is applied in the differential operation. The circuitry is operated in such a manner that the pulses in the photomultiplier (PMT) are limited at a few tenths of a volt. Data concerning the sensitivity and time-resolution properties of the system are presented.

The Pulse Limiter

The main effort in this work has been directed towards limiting the PMT pulse. It was shown by Post and Schiff that the time fluctuations inherent in the appearance of scintillation-counter pulses can be made smaller if fewer of the first photoelectrons appearing are utilized in forming a pulse.[1] Morton, treating the problem more generally by taking the transit-time spread of the PMT also into account, showed that, depending on the circumstances, there is an optimum number of the photoelectrons to be utilized, and that this number still amounts to a rather small fraction of all the photoelectrons available in one flash.[2,3]

It is easy to limit the PMT pulse heights by driving the control grid of a high-transconductance tube (e.g., pentode) to the cutoff region. However, working near cutoff in order to perform the limitation at small amplitudes makes the transconductance small and results in a small output amplitude. To maintain the output amplitude at a level high enough to operate the coincidence circuit, one usually compromises by cutting the PMT pulses at a few volts.[4,5]

In this work the pulse limiting was set at a few tenths of a volt. This was possible because

(1) the coincidence circuit (to be discussed later) requires only a few tenths of a volt input for successful operation;

(2) a distributed amplifier was used after the pulse former; there is no objection to slowing down the operation or introducing time uncertainties, since the amplification is applied after the pulse forming;

(3) the high-transconductance secondary-emitter tube EFP60 was used to perform the limiting.

The circuit diagram of the limiter is shown in Fig. C1. The circuitry is conventional. The

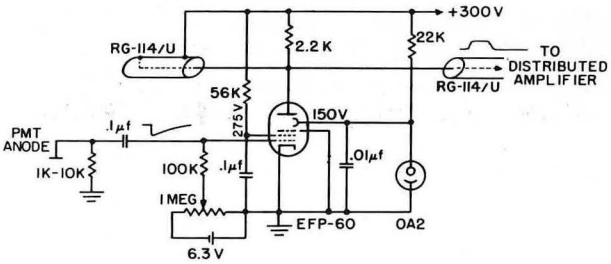

Fig. C1. The pulse-height limiter circuit.

bias setting of the first grid controls the steady current of the tube and determines thereby the height at which the limiting action is performed. This height was measured by replacing the PMT by a mercury-switch pulser (Electrical and Phys-

[1] R. F. Post and L. I. Schiff, Statistical Limitations on the Resolving Time of a Scintillation Counter, Physical Review *80*, 1113 (1950).

[2] G. A. Morton, Time Resolution of Scintillation Counters, Nucleonics *10*, 39 (1952).

[3] G. A. Morton, Recent Developments in the Scintillation Counter Field, in Report of International Conference on the Peaceful Uses of Atomic Energy, 1955.

[4] G. C. Neilson and D. B. James, Time of Flight Spectrometer for Fast Neutrons, Rev. Sci. Instr. *26*, 1018 (1955).

[5] R. E. Green and R. E. Bell, Notes on a Fast Time-to-Amplitude Converter, Nuclear Instr. *3*, 128 (1958).

ical Instrument Corp. Square Pulse Generator, Mod. 200). In the experiments presented here the limiting action was set to 0.3 v, corresponding to a steady anode current of 0.7 ma and a transconductance of about 2,400 μmho. The transconductance of the EFP60 is given as g_m = 25,000 μmho at an anode current of 20 ma, so that only about one-tenth of that is utilized here, working near cutoff.

The output pulses of the EFP 60 are clipped to ~ 20 mμsec by a shorted line made of RG-114/U 180-ohm cable, and enter a distributed amplifier (Hewlett-Packard Model 260).

The operation of the limiter on PMT pulses (RCA 6810A operated at 1800 volts) excited by the gamma pulses of Ni^{60} in the plastic scintillator (Pilot Scintillator B) is shown in Fig. C2. The pulses are photographed as they appear on the screen of a 517 Tektronix oscilloscope. The height of the shaped pulses is ~ 0.5 volt. On the left side of the tracks are seen the dark-current singles of the PMT, which are too small to drive the EFP60 into cutoff and which do not trigger the scope. Comparing the average pulse height of the singles with that of the formed pulses, one sees that only a few photoelectrons (< 10) participate in the forming of pulses which enter the coincidence circuit. One also sees that the formed pulses display little amplitude spread.

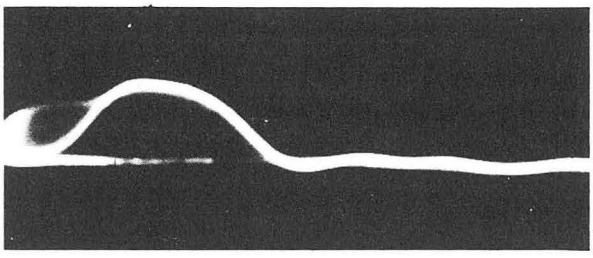

Fig. C2. Scintillation pulses after forming.

The Coincidence Circuit

To measure the overlap between coinciding pulses, we used the diode bridge coincidence circuit as developed in our earlier work, applied in the differential coincidence operation.[6,7] The diagram of the coincidence circuit, as used in a simple coincidence operation (called C operation) is reproduced here in Fig. C3. The circuit used in the differential coincidence operation (called

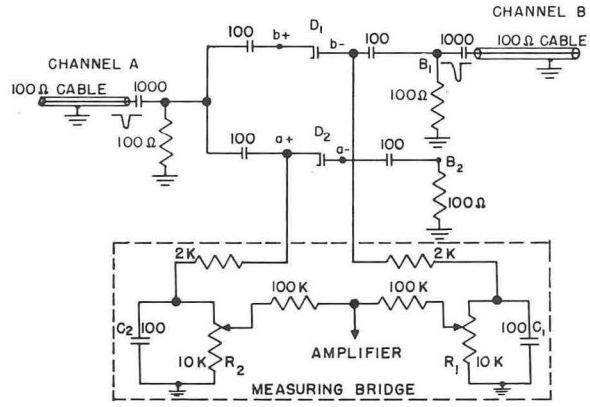

Fig. C3. Diode bridge circuit in simple coincidence operation.

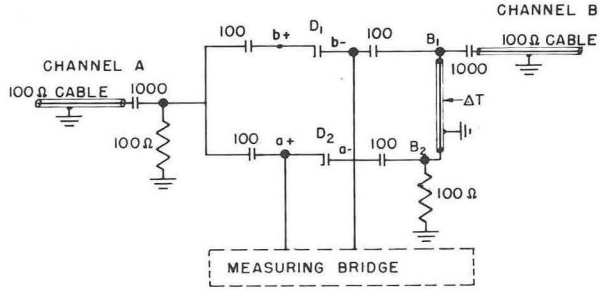

Fig. C4. Diode bridge circuit in differential coincidence operation.

D operation) is as shown in Fig. C4. The cables and matching resistors have been changed to 180 ohms in this work. In the C operation, the output is proportional to the overlap between pulses; in the D operation the output appears as the difference of the outputs of two C circuits, which are shifted against each other by a constant time delay. Therefore, depending on the time delay between the input pulses, the resulting output is of one sign (say, positive) at some given time delay, decreases with increasing time delay, goes through zero, and becomes negative, its amplitude increasing with increasing time delay. The slope--change in amplitude vs change in time delay--is in this way twice as much as in the C operation. This more sensitive response of the circuit to a change in time delay makes the D operation preferable for the use in time-delay—to—amplitude conversion. An additional advantage is that the sign of the output tells which of the input pulses is earlier.

In the older use of the circuit, in which the coincidences were counted in an all-or-none fashion, the linear response of the output amplitude to time delay was not essential. To check the circuit in this respect (for use as a time-delay—to—amplitude converter), we used the square shaped pulses of the pulser mentioned

[6] Z. Bay, Millimicrosecond Coincidence Circuits, Nucleonics *14*, 56 (1956).

[7] Z. Bay, Techniques and Theory of Fast Coincidence Experiments, IRE Transactions on Nuclear Science, Vol. NS-3, 12 (1956).

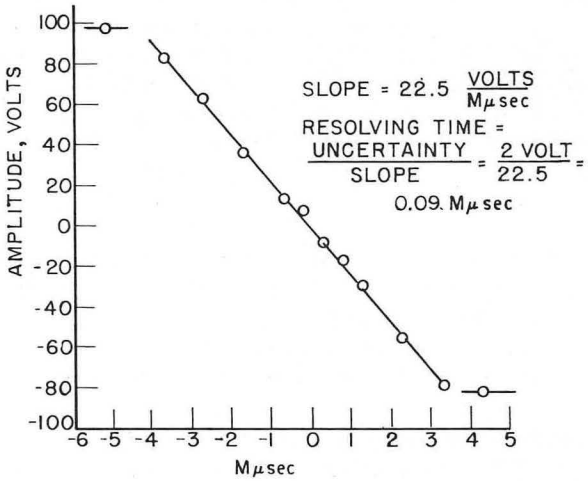

Fig. C5. Response of the differential coincidence circuit to branched square pulses.

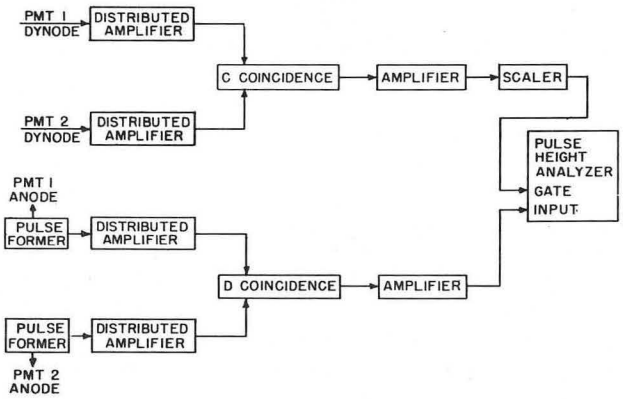

Fig. C6. Block diagram of the converter.

above, branching them into two coincidence channels. The response of the circuit is shown in Fig. C5. The abscissa is time delay as meaured by lengths of cable inserted in one of the channels. The measured points lie on a straight line, the average deviation being not more than 2 volts. This gives a time uncertainty of 0.09 mμsec in the time-delay—to—amplitude conversion with the slope of 22.5 v/mμsec. It is interesting to note that at a given time delay all the output-pulse amplitudes fall within a 1-volt channel of the pulse sorter, showing that the resolving time of the equipment is less than 5×10^{-11} sec. The rest of the deviations are probably due to some ringing superimposed on the square shape of the pulses.

The block diagram of the equipment is shown in Fig. C6. One sees that, besides the D circuit used as the converter, another coincidence circuit in C operation is incorporated, preferably driven by the dynodes of the two PMT's. This circuit is set to a sufficiently long resolving time to respond to all coincidences (even with the longest time delays) involved in the experiment. The output of this circuit gates the pulse sorter accepting the output pulses of the converter. Therefore, only those coincidences are analyzed which also make a coincidence in C.

The use of this C circuit was taken from our earlier coincidence work. In the single-channel coincidence operation, the C circuit gives the total coincidence counting rate (see Section IV of Ref. 7), monitors the equipment, restricts chance coincidences to the time-delay range of the experiment, and provides for a normalization factor to draw the reduced coincidence curves. The ordinates of the reduced coincidence curves are given in fractions of the total C rate and it was shown that the area under such a curve equals twice the resolving time of the circuit, while the width of a prompt curve together with the resolving time permits the determination of the rms of the time jitters involved in the experiment.

In the time-delay—to—amplitude conversion operation, the C circuit serves the same purpose but in addition provides for sorting out the small pulses of the PMT pulse-height distribution which are below the level of satisfactory pulse shaping and which would give erroneous outputs from the converter. It should be noted that when a post-coincidence selection is applied that selects singles for which a satisfactory pulse forming is provided by the limiter, the C circuit may not be needed. If the pulse sorter of the converter operates with adjoining channels, then every coincidence shows up in one of the channels and the total coincidence rate is simply given by the sum of the rates in the individual sorter channels.

Results

The equipment was tested by using the prompt gamma-gamma coincidences of Ni^{60} with the pulse limiters set to 0.3 v in both counter channels and giving inputs to the D converter as shown in Fig. C2. The time resolution of the C circuit was set to ~ 7 mμsec (half width at half maximum). The coincidence curve taken with the discrimination level of the C circuit set to 5 v is shown in Fig. C7. This curve is the spectrum on the pulse-height analyzer converted to time scale by the calibration curve shown on the right-hand side of Fig. C7. It is estimated that the setting for C at this level corresponds to the energy level of ~ 250 kev of the Compton

distribution in the scintillators; i.e., all flashes above this energy level contribute to coincidences. At this setting of the C discriminator it was found that all the pulses were properly limited. The channel width of a 10-channel Denver (Model 103) pulse-height analyzer was set to 2 v. The coincidence curve has a half width at half maximum $\tau' = 0.69$ mμsec, and the resolving time is τ - 0.15 mμsec, giving $\hat{t} = 0.47$ mμsec for the rms time jitter as related to one coincidence channel.

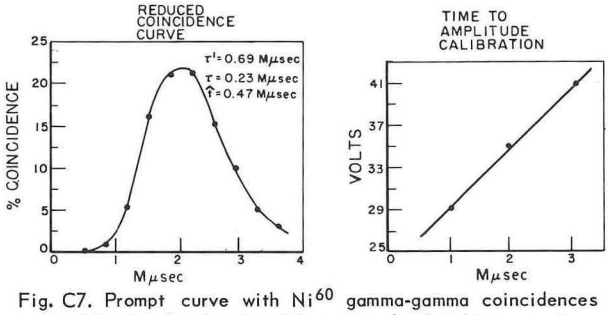

Fig. C7. Prompt curve with Ni^{60} gamma-gamma coincidences and calibration for the time-delay–to–pulse-height conversion.
Erratum: $\tau = 0.23$ mμsec should read $\tau = 0.15$ mμsec.

The results indicate a satisfactory performance of the circuitry. The best result we obtained earlier was $\hat{t} = 0.35$ mμsec for Ni^{60} gamma-gamma coincidences.[8] The $\hat{t} = 0.47$ mμsec reported here is near this. It is important that the good time resolution is obtained without any narrow selection of amplitudes in either of the coincidence channels; i.e., with a high coincidence efficiency. An improvement in $\hat{t}$ at the present efficiency may be achieved by better utilization of the features of modern PMT's. This is now under investigation.

Discussion

It is shown elsewhere[8] that the time uncertainty in the position of the centroid of a prompt-coincidence curve can best be obtained in the single-channel coincidence operation as

$$V(\mu_1) \sim \frac{2K\,\hat{t}^{\,2}}{C\,[T]}\,, \qquad (1)$$

[8] Bay, Henri, and Kanner, Statistical Theory of Delayed-Coincidence Experiments, Phys. Rev. *100*, 1197 (1955).

where $V(\mu_1)$ is the variance of the coordinate of the centroid; $\hat{t}$ is the resulting rms of the time jitters (originated anywhere in the equipment including the scintillators, light piping, PMT's, and the circuitry); C is the total coincidence counting rate; [T] is the total time of observation spent for counting at the successive points of the curve; and K is the range of the measurements in units of the width of the curve (usually $K \sim 3$). The value of $V(\mu_1)$ sets the limitation in the determination of very short decay times (shorter than the width of the curve). Equation (1) is obtained as an optimum when the resolving time of the circuitry equals the rms time jitter.

In case of time-delay—to—amplitude conversion, which is equivalent to a multichannel coincidence system, Eq. (1) changes to

$$V(\mu_1) = \frac{\hat{t}^{\,2}}{C\,[T]}\,, \qquad (2)$$

provided that the resolving time is small compared with $\hat{t}$--a condition that is easily fulfilled if the channel width of the kick sorter is somewhat smaller than $\hat{t}$.

There are two interesting conclusions to be drawn from Eqs. (1) and (2). One is that for good accuracy in the time measurements, $\hat{t}^{\,2}/C$ has to be small. In other words, the time-resolution properties of a coincidence circuit have to be judged always in connection with coincidence efficiency. The second point is that the time-delay—to—amplitude conversion, as compared with the best use of the single-channel coincidence circuit, decreases the statistical error in short time measurements by $\sqrt{2K} \sim 2.5$ if the same time of observation is used, or decreases the time of observation needed to achieve the same accuracy by $2K \sim 6$. This "speeding up" by a factor of about 6 may look too small at first sight, since one is inclined to think that the gain in time of observation is simply measured by the multiplicity of the channels. The explanation lies in the fact that it is of little help to use channels very much narrower than those corresponding to the rms of the time jitters.

C-2. TIME—TO—PULSE-HEIGHT CONVERSION

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Oak Ridge National Laboratory
Oak Ridge, Tennessee

I will start by describing one application of time—to—pulse-height conversion with the hope that it will stimulate the builders of such circuits to make them more stable and capable of taking higher counting rates, because some uses require a different accent than ultraspeed. Then I shall briefly describe one version of such a circuit, which also has some other desirable attributes.

Figure C8 shows, schematically, the arrangement we are using to make neutron total cross-section measurements in the kilovolt range by time of flight.[1] The proton beam is pulsed, before acceleration, at a repetition rate of 600 kilocycles per second, with a burst full width at half maximum of about 5 to 6 mμsec. The pulsing is performed by sweeping the focused beam from the ion source across an aperture at the entrance to the accelerator tube. The ion source is capable of supplying continuous currents of 400 to 500 ma of H^+, so that with a duty cycle of ~0.5% the average target current is 2 to 3 μa. The (p,n) reaction in the Li^7 target serves as the neutron source. The detector is a B^{10} slab combined with a NaI(Tl) crystal which views the 480-kev gamma ray from the $B^{10}(n,\alpha\gamma)Li^7$ reaction. The time—to—pulse-height conversion system provides multichannel time analysis. With the beam focused into the usual 1/8-inch-diameter spot we are able to work with separated nuclides in 1/10- to 1/20-mol quantities.

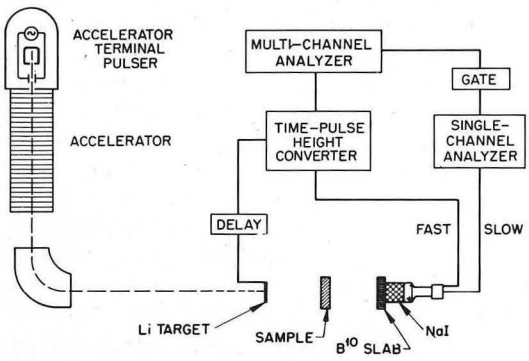

Fig. C8. Time-of-flight apparatus.

[1] Good, Neiler, and Gibbons, Phys. Rev. *109*, 926 (1958).

The center-of-mass motion in the $Li^7(p,n)$ reaction near threshhold results in two neutron groups, which are shown in Fig. C9. In this particular figure the gamma rays from the target would occur off scale near pulse height 1200 to 1400. The transmission measurement is performed in the region of the lower-energy group, the exact position of which is adjusted to provide maximum intensity and optimum resolution for each particular analyzer "bite." Figure C10 is a typical cross-section curve obtained by this method. Actually it is probably our best typical curve so far. The resolution appears to be around 2 to 3%, which roughly checks what we would have predicted from our estimated time resolution of 1 to 1.5%.

Figure C11 shows the simple-minded time—to—pulse-height converter presently in use. It operates by having the detector signals cut off a pentode, the output of which is clipped and then lengthened by diode D_1. The lengthened signal turns on a constant-current tube which dumps charge into the input of a linear amplifier. After the delayed beam pulse comes along, it discharges the lengthener by opening up V_3 and thus stops the constant current. The advantages of this circuit are that you can control the currents in tube V_1 with relatively low-level

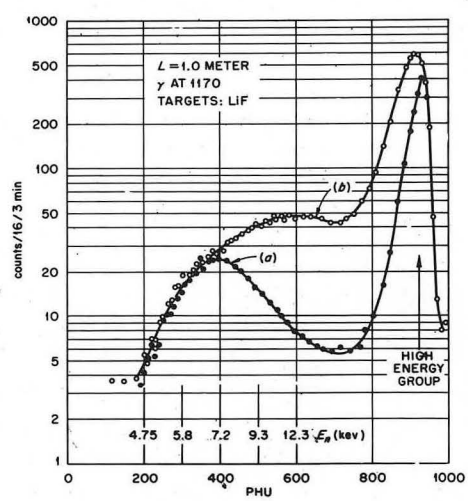

Fig. C9. Primary neutron spectrum used for kev total-cross-section measurements.

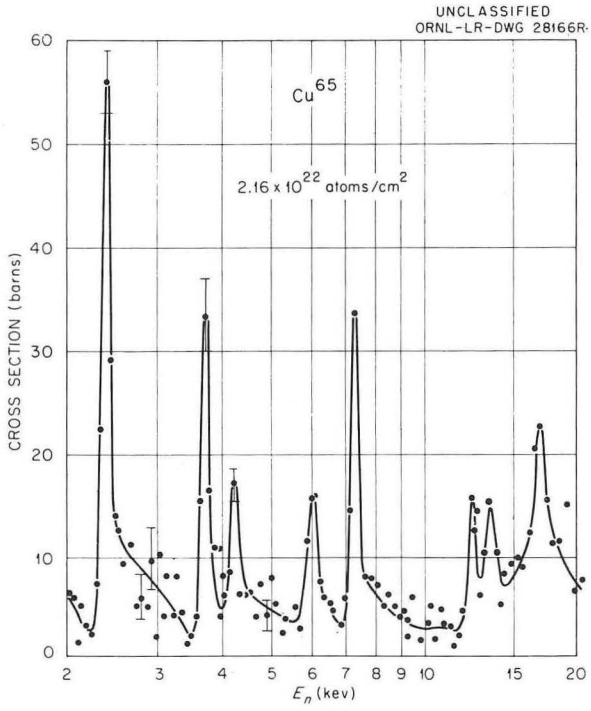

Fig. C10. Neutron total cross section of Cu^{63} measured by fast time of flight.

signals, such as 10-stage photomultiplier outputs after distributed amplification, and you allow the linear amplifier to be the smart thing in the circuit. A good linear amplifier can handle high and rapidly fluctuating counting rates with not too much trouble from pile-ups. This method does have difficulties. One, it is not a good circuit for taking care of the problem of timing "walk" with pulse amplitude that occurs with slow-decay-time phosphors. Two, it is not really a high-counting-rate circuit. The time—to—pulse-height circuit doesn't do too badly at 20,000 counts per second, but the linear amplifier is beginning to suffer.

A solution to the problems of high counting rates and of timing walk has been worked out

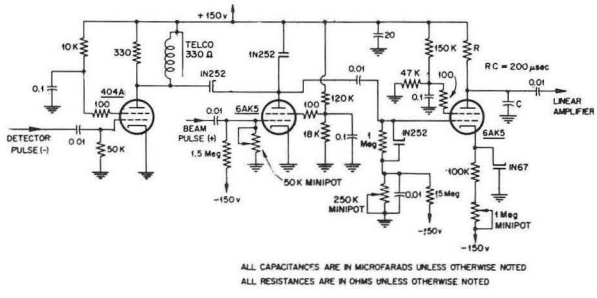

Fig. C11. Circuit diagram of simple time-to-pulse-height converter.

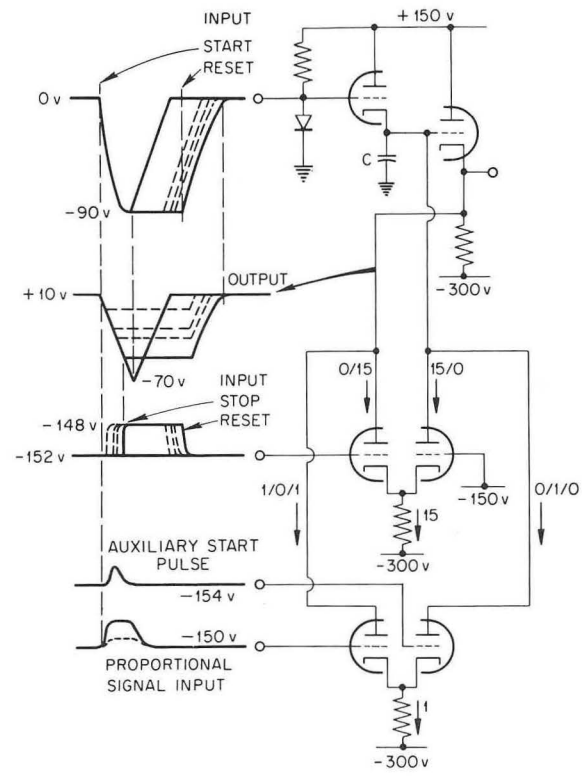

Fig. C12. Basic principles of improved time—to—pulse-height converter.

by Dan Maeder, who has been at Oak Ridge for the last year or so. I would like to try to describe his circuit,[2] the basic principles of which are illustrated in Fig. C12. This is a circuit that does all the things the simple circuit does, plus some. It takes care of high counting rates and should handle rapidly fluctuating rates; provides a high-output-level signal, so that you aren't limited by linear amplifier resolution; and, we hope, will work on the first photoelectron (or thereabouts) of the NaI(Tl) signal so that you can get the ultimate in timing resolution. Operation is initiated by a start signal from the detector, which turns off a clamp tube connected to the condenser C, and starts a linear charging of the condenser. At the time determined by the flight time and circuitry delays, the charging is stopped by the arrival of the stop pulse which transfers the charging current from the constant-current tube to its counterpart, leaving the signal stretched so that analysis may be performed. If the signal goes to an upper level without being stopped, an automatic reset operation takes place to prevent paralysis of the circuit should no stop signal come along. There

[2] To appear in ORNL Annual Report for Period Ending March 10, 1959.

are quite a few auxiliary functions that have to be performed to permit handling of high counting rates and use of the signal by an analyzer. There must be produced an output trigger signal which tells the analyzer that there has been a useful stop signal and that it may initiate the analysis process. In turn, the analyzer must provide a reset signal to turn on the clamp tube after analysis and thus ready the circuit for the next detector signal. Other functions that must be performed are inhibition of the clamp-tube cutoff and of stop-pulse operation during the reset cycle.

All the above was necessary to handle the high counting rates, and to provide good resolution on relatively slow signals where nonlinear operation is necessary,[3] although the energy range allowable for the input signals would still be greatly limited if no other steps were taken. This circuit, however, provides a method of correcting the "walk" so that a rather wide range of input-signal amplitudes may be used. By "walk" I mean the variation of the effective cutoff time of the clamp tube due to the way in which the mean time for arrival of the first photoelectron varies with signal amplitude. The output signal needs correction by an amount dependent on the detector-signal amplitude and phosphor decay time. This is accomplished by having the auxiliary start pulse add a correction the converter output. The amount of this correction decreases with increasing amplitude of the detector proportional signal, which is fed to the other input of the differential amplifier. Thus you can adjust both the amount of the walk correction and the range of signal amplitudes for which the correction is made.

The performance of this circuit has been tested with detectors providing both start and stop signals. The result is shown in Fig. C13, which is an oscilloscope plot of the amplitude of the NaI(Tl) start signal (as ordinate) against time interval converted to amplitude (as abscissa). The stop-signal amplitude, which is just the raw signal from a plastic phosphor, is not plotted. The scope has been intensified during the stretched portion of each signal. The bright region is due to coincident annihilation radiation in the two detectors. You may be able to see also some 1.28-Mev gamma rays which were in

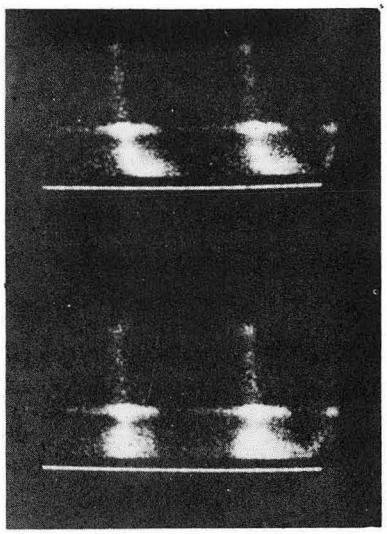

Fig. C13. Two-dimensional record of pulse amplitude versus delay time distribution. Two groups of delayed coincidences have been obtained from a Na^{22} source by inserting two different lengths of delay cable between the "stop" channel detector (a plastic scintillator on a 6810 A tube) and the time-to-voltage converter. Vertical deflection displays pulse amplitudes in the "start" channel detector (a NaI scintillator on a 6810 A tube).

coincidence with one of the annihilation quanta. The timing walk is quite evident in the upper pair of spectra, which are spaced ~ 30 mμsec apart to provide a time scale. In the lower set the correction has been applied to eliminate this walk. The spectrum on the right shows a little bit of overcorrection. A true multidimensional analyzer would be quite useful here; it is quite difficult to measure the resolving time from this picture. Other measurements with fast scintillators in both sides have shown a full width at half maximum of 3 mμsec.

Discussion

Gatti: It is quite misleading to speak about cutting off with one or two or three photoelectrons; in fact, generally these electrons are distinguishable only at the photocathode and don't have time to deliver independently the full charge at the output. Generally one cuts off the tube with a weighted contribution of different electrons coming out from the phosphor.

[3] Colombo, Gatti, and Pignanelli, Nuovo cimento (10) 4, 1550 (1956).

C-3. MANY COINCIDENCE CHANNELS

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"Hodoscoping" a large array of counters in coincidence with a gate pulse is an old cosmic-ray technique. This talk deals with the problem of hodoscoping a large array of counters in a machine experiment.

Figure C14 shows the desired sequence of operations. Gating should be fast; writing down the information contained in one gate, however, can be comparatively slow. For instance, in a 10-day run on the Bevatron, 10^7 events can be written during the machine pulses with a writing time of 1 msec.

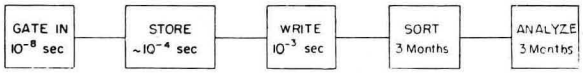

Fig. C14. Multichannel coincidence rig.

Figure C15 shows the block diagram of a recording unit that could be used for the counters. The input pulses are put in coincidence with a gate pulse, and the output coincidence is stored in a flip-flop until a reset pulse, following the gate pulse by a predetermined delay, resets the flip-flop. The readout can be by means of a light, a relay closure, or a magnetic tape-recording head attached to the flip-flop output. The information could also be read into temporary storage and all the time between pulses utilized for the readout process.

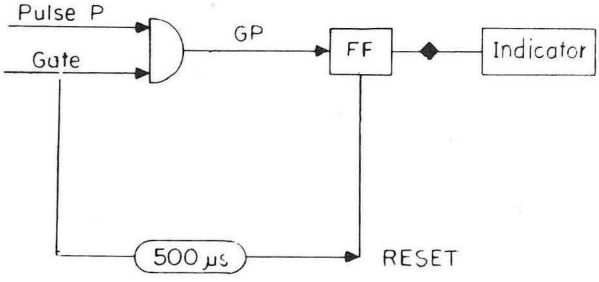

Fig. C15. Simple unit.

An MIT group is building equipment for an experiment which will involve about 200 counters and 300 coincidence channels.

Figure C16 shows the circuit diagram for the operations described in Fig. C15. It consists of an amplifier, a transistor Rossi gate circuit, and a flip-flop. It is driven directly from the output of a ten-stage phototube (6199 or 655A). The resolving time is about 1.5×10^{-8} sec and a 0.2-v input pulse is needed for operation.

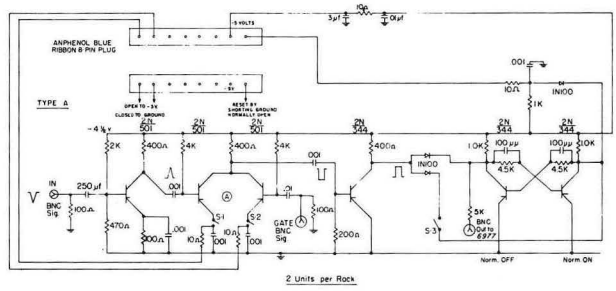

Fig. C16. Hodoscope flashing unit.

One hundred coincidence units can be mounted on one standard relay rack. The units can be ganged together so that the Rossi coincidence circuits can be switched "in and out" from one switch. Also the flip-flop resets are ganged together. For test purposes the flip-flop can be switched so that it will complement and function as a scale of two.

The output will be recorded on 35-mm film (Cineflure Green Film) by photographing Amperex 6977 transistor indicator lights directly connected to the flip-flop. The film will be run continuously at speeds of the order of 2 feet per sec during the machine pulse, and the indicator lights will record as a line of dots on the film. It appears quite feasible to write a hundred bits of information in one line in 500 μsec. It is hoped that the film can later be read electronically, possibly by scanning the lines of dots with a television camera sweep.

The commercial cost of such coincidence channels is about \$90, the cost of ten-stage phototubes about \$40, and plastic scintillators about \$20. The cost of one unit of information in a large counter array probably lies in the range of \$100 to \$200, depending on exact design. Naturally it is hoped that the data from a typical experiment can be largely analyzed directly with standard computer techniques.

C-4. MULTIDIMENSIONAL PULSE-MEASURING TECHNIQUES

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Oak Ridge, Tennessee

1. Need for Multidimensional Pulse Spectrometers

Two-dimensional coincidence methods have proved valuable in clarifying nuclear decay schemes. Consider, as an example, the γ rays emitted in a decay involving many excited levels. A complete investigation of γ-γ coincidences demands that each of the individual γ rays be selected in turn as the coincidence partner for the coincident spectrum displayed. However, all such information can be gathered in a single run if a two-dimensional (abbreviated 2-D) spectrometer is available. A 2-D plot of γ-γ coincidences from a Ga^{67} source is reproduced in Fig. C17.[1] This example was chosen to show that, as soon as a 2-D display is available, it becomes feasible to introduce a third variable--in this case a delay in one of the coincidence inputs. The difference between the prompt and delayed γ-γ energy spectra in this example proves the existence of a 90-kev metastable level. To establish its half life, a series of similar measurements at different delay times must be made. As the source half life was barely long enough for collection of sufficient data for these two 2-D runs, a 3-D spectrometer would have been far better for this experiment.

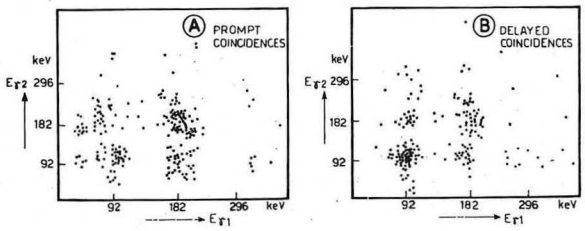

Fig. C17 Two-dimensional spectrometry based on dot recording: γ rays from the decay $Cu^{67} \rightarrow Zn^{67}$ are investigated by using two NaI scintillation crystals in a coincidence arrangement. (A) Prompt coincidences between 206- and 182-kev and between 206- and 90-kev γ rays show that the 388-kev level in Zn^{67} (known from the Ga^{67} decay) is excited. (B) Trigger pulses associated with vertical deflections have been delayed by 1.5 μsec ahead of the coincidence mixing (window width increased to 1.0 μsec) in order to detect delayed coincidences between $E_{\gamma 2} = 296$ (or 90) kev and the 9-μsec isomeric γ ray of $E_{\gamma 1} = 92$ kev.

Some variables that have frequently been combined in 2-D experiments are

E_γ, γ-ray energy (measured by inorganic-scintillator pulse amplitude),

E_β, β energy (measured by organic-scintillator pulse amplitude).

E_p, meson or heavy-particle energy (measured by proportional counter or thin scintillator),

$\frac{dE_p}{dx}$, specific energy loss (measured by proportional counter or thin scintillator),

T, time of flight for neutrons (detected via a recoil particle, or a γ ray from a radiator), or for charged heavy particles, including fission products (detected by a scintillator pulse).

Many 3-D combinations may permit otherwise impossible experiments--for instance, for measuring

T_n, $E_{\gamma 1}$, and $E_{\gamma 2}$ for neutron-capture γ-ray cascades;

T_{f1}, T_{f2}, and E_γ for fission γ rays.[2]

For truly multidimensional examples, we need only to look around the lab at Berkeley.[3] Recent high-energy experiments involve up to 20 counters whose individual pulse amplitudes are of interest in the evaluation of coincidences. After what we have heard earlier today, we may also list track lengths, angles, and positions in track chambers as future candidates for multidimensional recording.

2. An Idealized Set of Requirements

Recognizing the general need for multidimensional pulse-measuring equipment, let us con-

[1] Beusch, Erdos, Maeder, and Stoll, Helv. Phys. Acta 30, 268 (1957).

[2] J. S. Fraser and J. C. D. Milton, Nucl. Instr. 2, 275 (1958).

[3] Coombes, Cork, Galbraith, Lambertson, and Wenzel, Phys. Rev. 112, 1303 (1958)

Table CI

Specifications for multidimensional pulse-measuring equipment

Parameter	Idealized specifications	Realistic specifications
D=number of dimensions (dimension index $d = 1, 2, 3, \cdots, D$)	100	$\geqslant 3$
K_d=number of channels in each dimension (channel index $k = 1, 2, 3, \cdots, K_d$)	10^3	$\geqslant 100$ for $d = 1$ $\geqslant 10$ for $d=2, 3\cdots$
$N_{k_1 k_2 \cdots k_d}$ = counting capacity in each d-fold coincidence channel	unlimited	$\sim 10^5$ (or $2^{16}-1=65535$)
R_d = maximum total counting rate in each dimension	limited only by characteristics of radiation detector	$\sim 10^5$/sec ($\sim 10^7$/sec during duty cycle of pulsed machines)
Dead-time correction	unnecessary	automatic correction
Presentation of results	print-out of final results in terms of fundamental parameters and a few checks of correct operation of equipment	recorded in a form that can be fed into computer for further analysis

sider the requirements that such equipment would have to meet in order to be universally applicable. Wishful thinking, with no regard to technical difficulties, might lead to the specifications given in the middle column of Table CI, although most present-day experimenters would probably be highly pleased with the more modest features suggested in the third column.

Evidently no one would foresee any circumstances under which all the desirable features would be exploited simultaneously. In particular, high counting rates are likely to occur in the measurement of single input pulses only, whereas d-fold coincidence rates are cut down by (D-1) efficiency and solid-angle factors ω_d, each of which is less than unity. However, a capability of high acquisition rates is desirable in order to permit one to evaluate the single-input spectra in the same apparatus as the coincidences of different orders, using only one experimental run to collect the complete set of information.

Similar considerations apply to the requirements in total count capacity. In the extreme example of a flat 3-D spectrum whose fluctuations are to be studied in $K_1 \times K_2 \times K_3$ channels to a 1% statistical accuracy, the minimum required number of counts per channel would be

$$n_{3\text{-fold}} > 10^4,$$

$$n_{2\text{-fold}} > \frac{K}{3\omega} \cdot 10^4 \ (=10^6, \text{ for } K = 30 \text{ and } \omega = 10\%),$$

$$n_{\text{single}} > \frac{K^2}{6\omega^2} \cdot 10^4 (= 1.5 \cdot 10^8, \text{ for } K = 30 \text{ and } \omega = 10\%)$$

(assuming, for simplicity, $K_1 = K_2 = K_3 = K$ and $\omega_1 = \omega_2 = \omega_3 = \omega$).

Various design principles can now be discussed in the light of our list of requirements.

3. Recording of Analyzed Distributions (Brute-Force Method)

The straightforward combination of a single-channel window with a conventional multichannel spectrometer is well known,[4] and could in principle be extended to more than two dimensions by using one single-channel selector with every additional dimension. However, the accumulation of data by such an arrangement would become extremely slow as the number of dimensions increased.

Better use of machine time or radioactive-source time could be made if the individual windows were replaced with a chain of channels in each dimension--provided that a sufficient number of scalers and registers were available to count pulses in each channel-channel-etcetera combination. A magnetic-core memory providing a 65535-count capacity in 64x64 channels would seem quite feasible but would still be limited essentially to 2-D work, except for cases that do not require any good amplitude resolution (e.g., that could be handled in a 64x8x8-channel arrangement). A system of 64x64 conventional

[4] P. R. Bell, in *Beta and Gamma-ray Spectroscopy*, ed. by K. Siegbahn (Interscience Publishers, New York, 1955), Chap. V, p. 7.

scalers seems out of the question, considering the excessive time consumed in readout. Even the punched-tape output to which magnetic-core memories have been adapted takes several minutes, during which the experiment is stalled.

While the straightforward recording in a multitude of physically built counting devices seems to promise a satisfactory solution for the general 2-D case, a much simpler photographic method has been found useful for qualitative 2-D work.[5,6,7] In a picture of a 2-D cathode-ray-tube display (as illustrated by Fig. C17), approximate intensities may be determined from photographic densities in as many as 10^4 channels. Although the accuracy at low and high densities becomes poor, the "counting capacity" is practically unlimited, and the structure present in a 2-D distribution is immediately brought to evidence.

4. Recording of Individual Events (Buy-Now-Pay-Later Method)

It is possible to use the 2-D photographic recording method for absolute measurements, simply by dividing a long experimental run into a series of exposures such that each picture shows only an easily countable small number of events (Fig. C17 has been composed from about 40 individual pictures). A step further leads us to multidimensional versions of the classical recording method using a steadily moving film. Recording of individual events is indeed the most rapid and flexible way of storing complex information. The big drawback, as indicated tentatively in the subtitle, lies in the labor of scanning such records in order to extract the information in a useful form at some later date.

A. Analog Recording

For extremely low counting rates a conventional multiple-input pen recorder could be used to write coincident pulse amplitudes on a moving paper chart. However, the scanning problem would make this method impractical anyhow.

Standard magnetic-tape units can handle about 10^4 periodic pulses per second in eight independent tracks (1/2-in.-wide tape); recent improvements bring this figure up to 5×10^4 per sec, or 500 random pps at 1% overlap loss. Scanning for magnetization intensity in carefully selected tapes reproduces the original pulse-amplitude distribution within about 3%, according to Cavanagh.[8] Thus, reliable 100-channel resolution in four dimensions should be possible on standard 1/2-in. tape used in a semianalog fashion, with units and tens assigned to two separate tracks for each dimension.

If random pulses were stored alternately in two fast electronic stretchers before being transferred to the high-speed tape, overlap losses could be reduced to 1% at about 5,000 input pps, at a cost of considerable circuit complexity. The tape space, instead of being 99% empty, would be 10% filled with information, and the scanning time for a given total number of events would be decreased by a factor of 10.

Photographic multidimensional recording can be performed either sequentially (see Fig. C18, left), displaying the different input signals via different delays on a fast single sweep,[3] or parallel (see Fig. C18, right), using a multiple-gun oscilloscope tube producing up to four traces simultaneously.[9] With both methods, overlap can be eliminated by means of a sawtooth signal applied to the horizontal cathode-ray-tube deflection system. Figure C19 shows how this artifice can simulate a quantized film motion, permitting

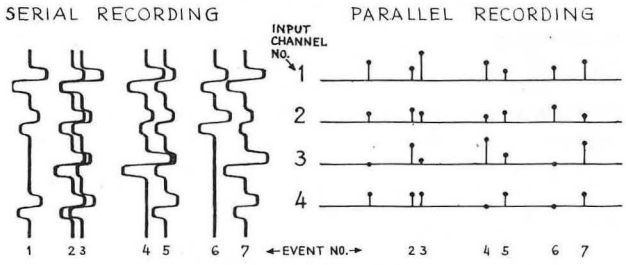

Fig. C18. Analog recording of multiple input pulses.

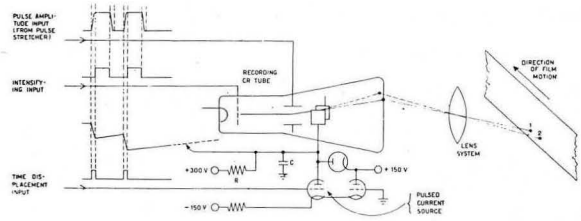

Fig. C19. Use of auxiliary cathode-ray-tube deflection to simulate quantized film transport.

[5] L. Grodzins, Rev. Sci. Instr. *26*, 1208 (1955).

[6] D. Maeder and P. Staehelin, Helv. Phys. Acta *28*, 193 (1955).

[7] Th. Mayer - Kuckuck, Naturforsch. *11a*, 627 (1956).

[8] P. E. Cavanagh and D.A. Boyce, Rev. Sci. Instr. *27*, 1028 (1956).

[9] H. G. Jackson, Rev. Sci. Instr. *29*, 527 (1958).

[10] D. Maeder, Nuclear Instr. *2*, 299 (1958); see page 305.

extreme economy in the use of storage space. Calculations show that the film could be 80% filled, with practically no risk of too large excursions on the cathode-ray-tube screen.[10] Film-transport speed in commercial cameras would thus permit recording as well as scanning rates up to 20,000 events per sec. Unfortunately, photoelectric scanners do not appear to be commercially available yet.

B. Digital Recording

The scanning problem is considerably simplified, and the number of available amplitude channels enormously increased, if the information is coded before it is recorded. Figure C20 shows how a coding circuit is fitted into the signal flow. With seven parallel outputs as shown in the figure, it would classify pulse amplitudes

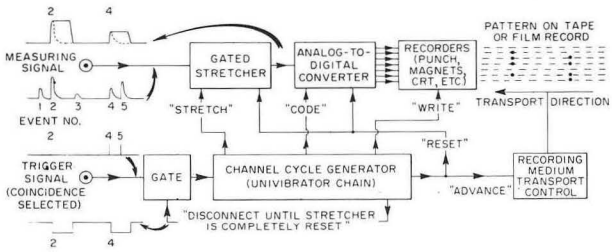

Fig. C20. Digital recording of pulse amplitudes from a single input channel.

into 127 channels. If the random occurrence of input pulses is smoothed as described under A (by use of two alternating fast memories), practical limits of acquisition rates are

$$N_p^{(7)} \lesssim 6/\text{sec for fastest punched paper tape,}$$

$$N_m^{(7)} \lesssim 5{,}000/\text{sec for fastest magnetic tape,}$$

$$N_f^{(7)} \lesssim 20{,}000/\text{sec for photographic film,}$$

assuming ideally fast coding circuitry. The simplest coding device, a CR tube containing specially shaped collector plates,[11] requires a processing time of a few mμsec.

Figure C21 suggests that multidimensional information should be recorded in time sequence, so that a single coding circuit would be sufficient. Punched-tape recording has actually been used with D=2 at Princeton[12] and D=3 at Chalk River.[2] With smoothing devices used as above, the per-

[11] L. A. Meacham and E. Peterson, Bell System Tech. J. 27, 1 (1948).

[12] Birk, Braid, and Detenbeck, Rev. Sci. Instr. 29, 203 (1958).

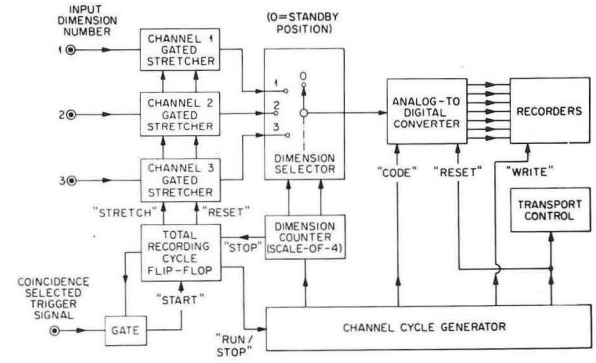

Fig. C21. Digital recording of multiple input pulses in time sequence.

missible d-fold coincidence rates would become $\frac{6/\text{sec}}{D}$ for paper tape and $\frac{5{,}000/\text{sec}}{D}$ for magnetic tape, but would still be still be 20,000/sec for film recording, since a single vertical row on a 35-mm film can easily accommodate all bits from many dimensions.

If, as seems desirable, not only d-fold coincidences but also coincidences of lower dimension and even single-input events are to be recorded in the same run, any intermediate storage system to aid the slow recording media would become extremely complex, involving the establishment of a "waiting list." Therefore the total number of events that can be recorded would practically be limited to

$$N^{(D)} + \sum N^{(D-1)} + \cdots + \sum N^{(1)},$$

$$\text{which is} \lesssim \frac{0.6/\text{sec}}{D} \text{ with paper tape,}$$

$$\text{or} \quad \frac{500/\text{sec}}{D} \text{ with magnetic tape.}$$

On the other hand, since a CR beam deflection enhancing the film-transport motion can easily be applied with each incoming signal of any di-

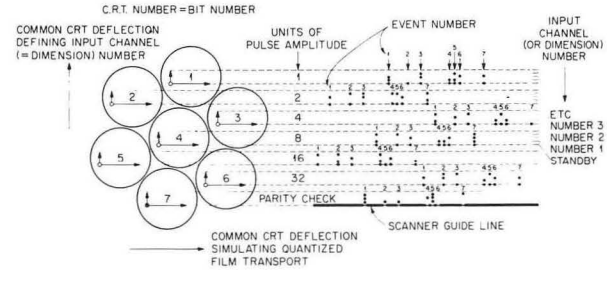

Fig. C22. Arrangement of cathode-ray tubes for film recording, and example of resulting pattern on film record.

mension, the total acquisition rate with film would still be

$$N^{(D)} + \sum N^{(D-1)} + \cdots + \sum N^{(1)} ,$$

or 20,000/sec with film recording.

A possible arrangement of seven miniature CR tubes for simultaneous exposure of the seven bits from a given input is proposed in Fig. C22. A vertical deflection signal corresponding to the position of the channel selector of Fig. C21 is applied to all CR tubes in parallel. For scanning, the same arrangement of CR tubes and camera would be used, with a phototube placed behind the film. A total of 10^7 events would require approximately 2,000 meters of film, which may be scanned once in less than an hour.

C-5. MEASUREMENTS OF MEAN LIFETIMES BETWEEN 10 mμsec AND LESS THAN 0.1 mμsec BY PULSED-BEAM TECHNIQUES

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Argonne National Laboratory, Lemont, Illinois
Presented by Frank J. Lynch

Pulsed-beam experiments can be considered as the special class of delayed-coincidence measurements in which the initiating event is produced periodically. Although the apparatus described here was originally developed to measure neutron spectra by time of flight, it is also suitable for the measurement of the lifetimes of excited states of nuclei. The excited states are produced by nuclear transformation of Coulomb interaction when a short burst of charged particles strikes the target. The time distribution of the gamma rays emitted in each transition from these states is then measured relative to the time of arrival of the burst of particles.

Figure C23 shows a block diagram of the equipment used. The beam from the 4-Mev electrostatic accelerator is deflected across a slit by an rf field so that bursts of particles are produced at the target with durations as short as 0.5 mμsec. In order to discriminate against unwanted gamma rays and neutrons, a detector with good resolution, NaI(Tl), is used. Either RCA-6810A or C-7251 photomultipliers are used with 10 stages of multiplication. As usual, two channels are used: a fast time-measuring channel and a slow pulse-amplitude channel. One time—to—pulse-height converter is of Los Alamos design[1] with some modifications by us; in the other the fast univibrator is replaced by an EFP-60 limiter with pulse shaping by a delay line in the dynode load. The time—to—pulse-height converter puts out a pulse whose amplitude is proportional to the difference in time between the pulse from the detector and the subsequent timing pulse derived from the peak of the rf beam-sweeping signal. A pulse from the converter is analyzed and stored in the 256-channel magnetic-core analyzer only if it is associated with a detector pulse whose amplitude falls within the window of the single-channel differential pulse-height analyzer.

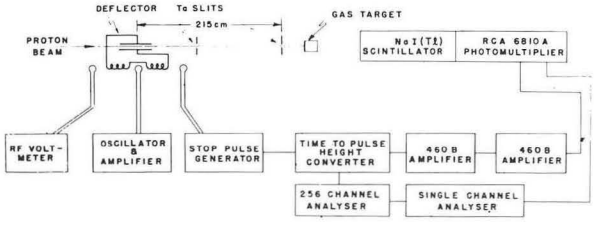

Fig. C23. Block diagram of pulsed-beam apparatus.

[1] Weber, Johnstone, and Cranberg, Rev. Sci. Instr. 27, 166 (1956).

Figure C24 shows the time spectra obtained for prompt gamma rays of different energies with either converter. The target was Al, whose several gamma rays above 1 Mev in energy are essentially prompt. The window of the single-channel analyzer is adjusted to admit pulses produced by Compton events in the crystal with energies in a band extending from 5% below to 5% above the energy shown on the curves. If the pulse amplitude did not affect the converter, one would expect all curves to start at the same time. The observed displacement of about 3 mμsec is due to the amplitude effects in the converter. This would be appreciably worse but for a diode

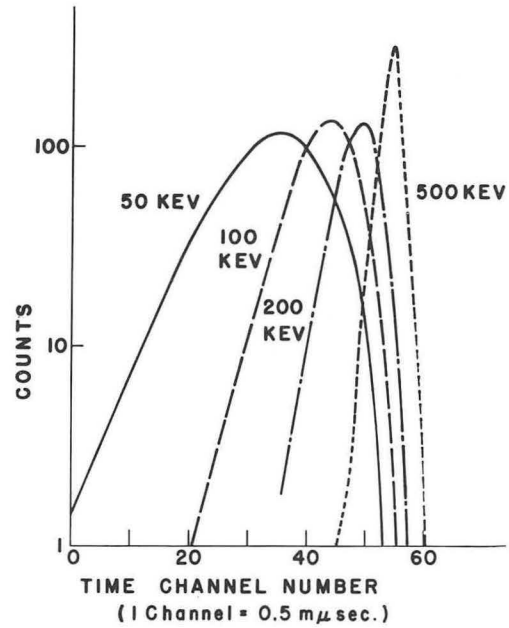

Fig. C24. Time spectra for prompt gamma rays of different energies.

load at the anode of the photomultiplier which compresses the dynamic range of pulses by a factor of more than 4. The remaining change in shape of curve with energy is due largely to the statistics of photoelectron production at the photocathode. From the Post and Schiff[2] formula for variation of average time with energy, and assuming a simple exponential decay in the scintillator of 0.25 μsec mean life, the triggering level appears to be about four photoelectrons at the photocathode.

Figure C25 shows the probability of arrival of the first, second, and third photoelectrons as a function of time, computed on the assumptions of a total of 65 photoelectrons (equivalent to about 30 kev) and a mean life of 0.25 μsec for the scintillations. The sharpest distribution would be obtained if the sensitivity of the time—to—pulse-height converter were sufficient to trigger on one photoelectron. However, to limit the counting rates from the thermionic current from the photocathode, the triggering level used is generally three or four photoelectrons.

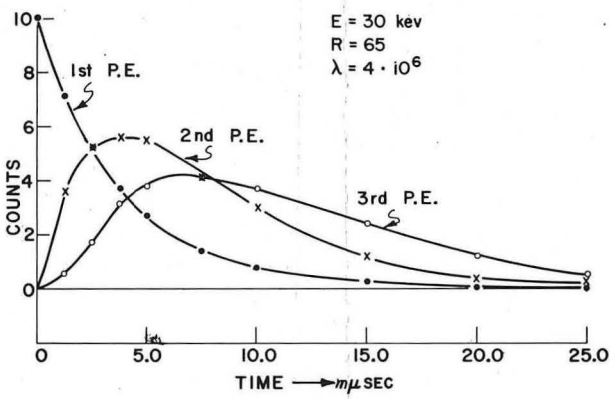

Fig. C25. Probability of arrival of first, second, and third photoelectrons as a function of time for a simple exponentially decaying fluor.

The following are some fairly typical lifetime measurements. Figure C26 shows the time spectrum for the 123-kev gamma ray produced by the transition from the second excited state at 137 kev to the first excited state in Fe^{57}. Since the lifetime is so long (11.5 mμsec), it is readily obtained from the slope of the tail on the semilog plot.

Lifetimes that are short in comparison with the resolving time of the system may be measured by comparing the time spectrum obtained

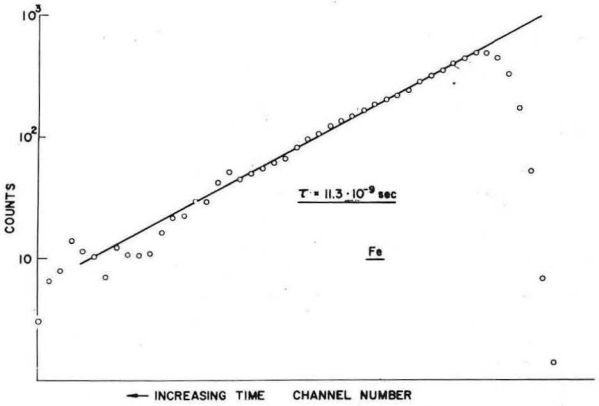

Fig. C26. Time spectrum of 123-kev gamma ray from second excited state of Fe^{57}.

for the gamma ray of interest with that obtained for a prompt gamma ray or x-ray of nearly the same energy. Figure C27 shows the time spectrum of the 30-kev gamma ray from the first excited state of K^{40} and that of the 26-kev Sn x-ray. The mean life was assumed to be that value of $\tau = 1/\lambda$ which best satisfied the convolution integral[3] $F(x) = K\int_0^x e^{-\lambda t} P(x-t)dt$, where F(x) is the measured "delayed" time spectrum, P(x) is the measured "prompt" time spectrum, and K is a normalizing constant. The same value of the mean life was calculated from the centroid shift between the two curves. The program has been prepared to carry out these calculations on the IBM-704 computer. A series of convolution functions F(x) is computed for different values of λ. The value of λ chosen is the one which gives the best least-squares fit between F(x) and the measured data.

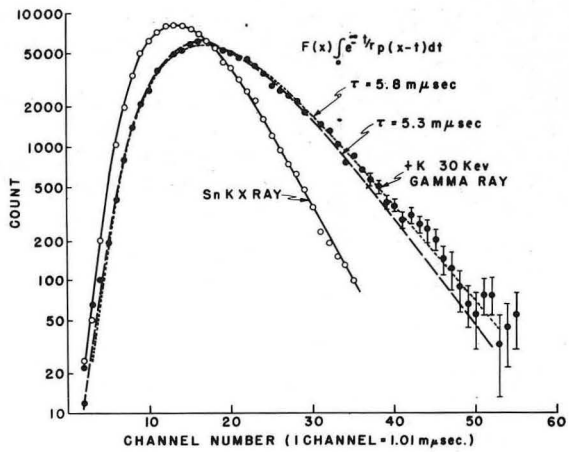

Fig. C27. Time spectra of 29.4-kev gamma ray from K^{40} and K x-rays of Sn.

[2] R. F. Post and L. I. Schiff, Phys. Rev. *80*, 1113, (1950).

[3] Bay, Henri, and Kanner, Phys. Rev. *100*, 1197 (1955).

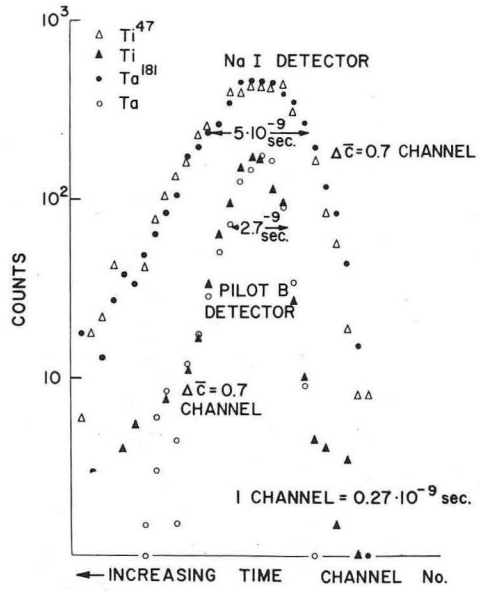

Fig. C28. Time spectra of 160-kev gamma ray of Ti^{47} and 136-kev gamma ray of Ta^{181}.

Figure C28 shows the time spectrum of the 160-kev gamma ray from the first excited state of Ti^{47} and that of the 137-kev gamma ray from the first excited state of Ta^{181}. The window of the single-channel analyzer was set at about 148 kev, about midway between the two photopeaks. The upper set of curves, taken with the NaI(Tl) scintillator, shows a full width at half maximum of 5 mμsec. Since there was only one gamma ray present from each target, the measurement could also be made with a plastic scintillator. The lower set of curves, taken with a Pilot B plastic scintillator, shows a full width at half maximum of about 2.7 mμsec. Both sets of curves show centroid shifts of 0.7 channel which, at 0.27 mμsec/channel, indicates a difference in mean lives of 0.19 mμsec. The lifetime of the Ta gamma ray, measured by comparison with Compton events produced by high-energy gamma rays from Al, was found to be < 0.1 mμsec. Indirect measurements of the lifetime indicate 0.017 mμsec $< \tau <$ 0.037 mμsec.

In order to measure lifetimes as short as a few percent of the resolution, care must be taken to avoid spurious centroid shifts. It is clear from Figs. C24 and C25 that a change in gain in the slow or fast channels will produce a spurious change in the time spectrum. The electronic gain in the slow channel is stabilized by negative feedback and the photomultiplier is operated with average anode currents less than 0.1 μamp to keep fatigue effects low. Narrow windows with a width of 5% to 10% are used on the single-channel differential pulse-height analyzer to minimize shifts caused by the difference in the centroid of the pulse-amplitude distributions within the window. However, the gain and sensitivity of the fast channel are not easily stabilized. In order to minimize the effects due to electronic and accelerator drifts, the targets are interchanged frequently during the course of a measurement. Control circuits automatically change the targets (and the position of data storage in the 256-channel analyzer) after a specified quantity of charge has reached the target. Considerable effort has been spent in minimizing spurious shifts arising from differences in counting rate in the fast timing channel. The major portion of this effect was corrected by minor changes in the analog-to-digital converter in the 256-channel analyzer. Difference in spatial distribution of scintillations in the crystal can also cause spurious shifts because of differences between the transit times from different portions of the face of the photomultipliers. To minimize this effect, we use a small crystal and photomultipliers with a low spread in transit time.

With the slow NaI(Tl) scintillator it is possible to measure mean lives down to 0.1 mμsec, probably with an error within ± 0.05 mμsec if sufficient care is taken. With a scintillator of equal energy resolution but shorter decay time, the limit of error can be proportionately reduced.

C-6. MILLIMICROSECOND GAMMA-RAY DETECTOR AND OSCILLOSCOPE SYSTEM

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Introduction

With the advent of high-energy short-pulse radiation sources, such as linear accelerators, there is a need for a high-resolution wide-dynamic-range detection and recording system. This paper discusses a single channel of a gamma-detection and -recording system which satisfies these requirements.

The equipment is capable of resolving radiation rise times of less than 1 mμsec. A single channel has a dynamic range of 30,000 and a band width of about 1,000 Mc.

Figure C29 shows how detection and recording channels are used for testing atomic devices. Detectors are positioned both near and far from the device. Signals generated in the detectors by the radiation released are transmitted by transmission lines into the recording blockhouse. The oscilloscope recording equipment presents the detected signals, and very sensitive film records the signal traces.

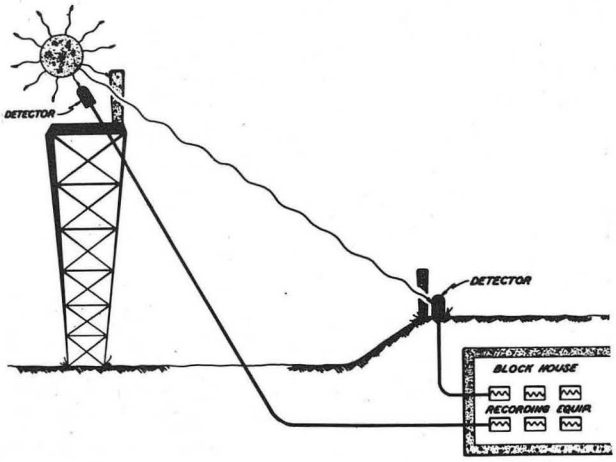


Fig. C29. Atomic instrumentation system.

* This work was performed for the Los Alamos Scientific Laboratory, and was sponsored by the AEC.

II. Principles of the System

Before the system is described, some of the principles involved in the development of this equipment should be explained. If a simple pulse, as shown in Fig. C30, is displayed on an oscilloscope, the band width of the oscilloscope system is given by unity divided by the time of the pulse. Thus, if a pulse 1 mμsec long is displayed, you have a 1,000-Mc system. This is the approximate over-all response of the system to be described.

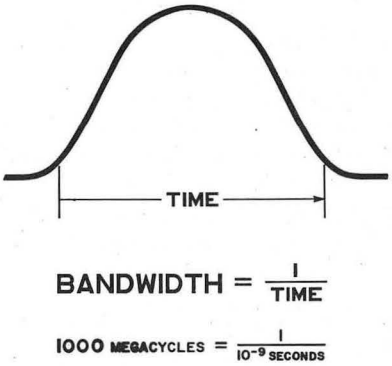


Fig. C30. Pulse and band-width relationship.

In an ordinary cathode-ray tube (Fig. C31), if you impress a fast pulse into the cathode-ray tube you will display a slow pulse out. The reason the pulse out looks as it does is the transit time

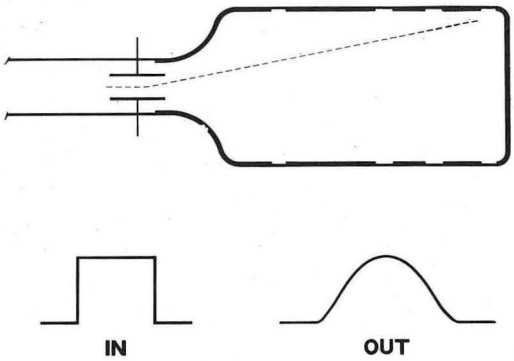


Fig. C31. Ordinary cathode-ray tube.

of the electron beam through the electrostatic deflection plates. A millimicrosecond pulse impressed on an ordinary cathode-ray tube would look like a slow pulse.

Figure C32 illustrates how the transit-time problem was improved. A cathode-ray tube featuring a traveling-wave deflection structure is used to deflect the electron beam. The signal is propagated down the deflection structure at the same velocity as the electron beam. Thus, the transit-time limitation of long electrostatic deflection plates is considerably reduced. Now if we impress a millimicrosecond pulse on a traveling-wave oscilloscope, we will see a pulse out similar to that in Fig. C32.

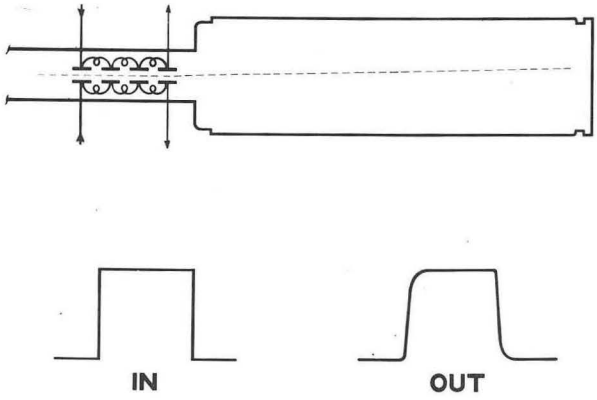


Fig. C32. Traveling-wave cathode-ray tube.

The performance of the cathode-ray tube has also been improved by increasing the sensitivity of the tube. This is described as the sensibility of the cathode-ray tube (Fig. C33), rather than sensitivity. To deflect the spot by one trace width requires a large voltage. The voltage required to deflect the cathode-ray tube by one spot width is termed the sensibility of the cathode-ray tube. If you took an ordinary cathode-ray tube and reduced the spot size to one-tenth, you would increase its sensibility by a factor of 10. If you reduce the spot size you can also reduce the spacing between the deflection plates and gain another factor of 2 or 3. Consequently, a total gain factor of from 20 to 30 over standard cathode-ray tubes can be achieved.

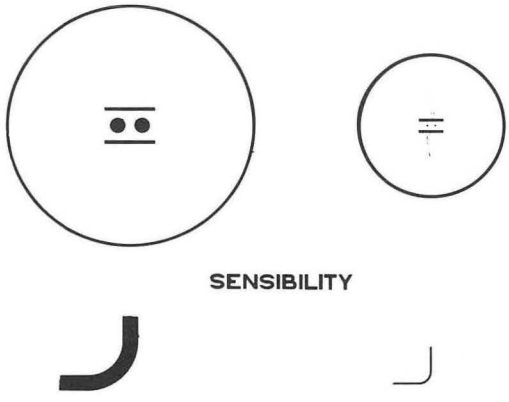


Fig. C33. Cathode-ray-tube sensibility.

The oscilloscope to be described has achieved this gain in this manner and is capable of displaying a 30-mv signal. Thus, 30 mv deflects the spot on the cathode-ray tube by one trace width (where a trace width is 0.0015 in. in diameter), producing a sensibility of 30 mv per trace width.

III. Single-Channel Detection and Recording System

Figure C34 displays a single detection and recording channel utilizing one detector and three oscilloscopes. A channel consists of the detector, transmission line, trigger tapoff, delay loop, inverter, and three oscilloscopes consisting of two Rossi-type sweeps and one linear-type sweep. An rf oscillator drives the sweeps of the two Rossi oscilloscopes, and a marker generator provides markers for the linear oscilloscope. The dots between the oscilloscopes are signal attenuators, either 5 to 1, or 2.5 to 1. The detector can deliver from one ma to 30 amp into the transmission line, which is a detection factor of 30,000. The oscilloscopes will display all the information from this single detector with a band width of a little less than 1,000 Mc.

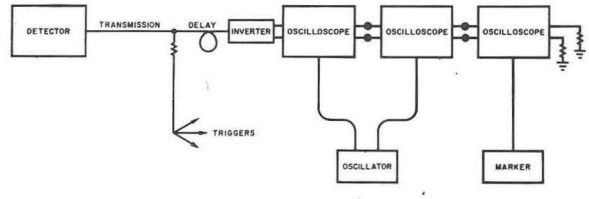


Fig. C34. Detector and oscilloscope system.

IV. Detectors

Figure C35 shows the detector and its mount. The detector is 5 in. in diameter. It normally operates at 9000 v, but can be operated at 20,000 v. Because of its compact design and high operating voltage, the transit time of light, of electrons, and of the signals is reduced so that the detector has a resolution of about 0.3 mμsec. The detector contains a coaxial photocell mounted in

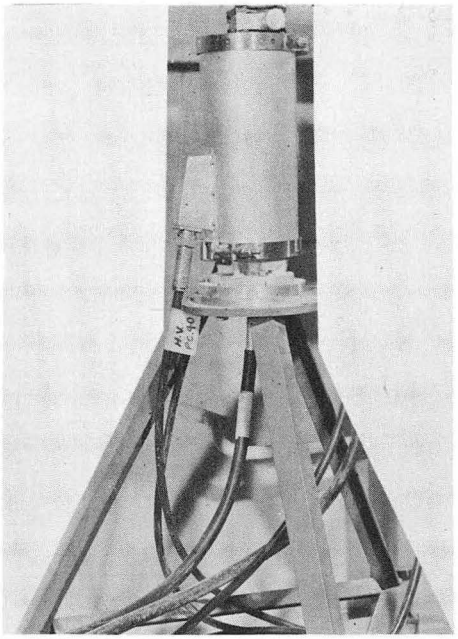
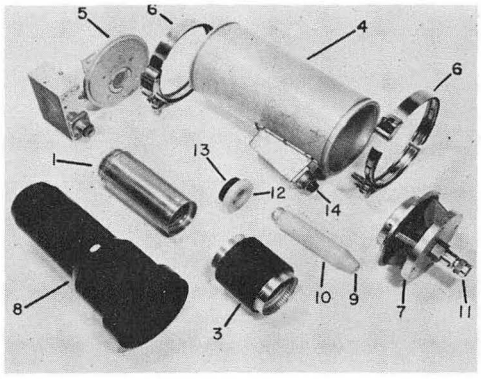
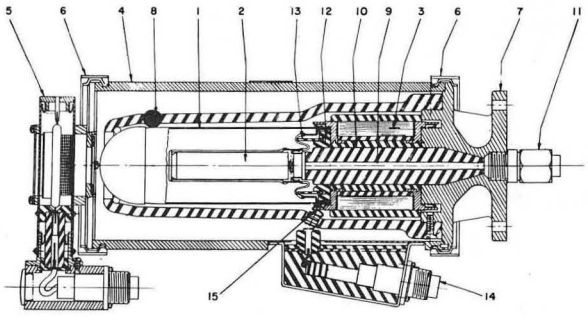


Fig. C35. Detector and mount.





Figs. C36 and C37. Breakdown and cross section of detector

1-PC-1A photocell
2-Scintillating material
3-High-voltage capacitor
4-Detector housing
5-Flashtube assembly
6-"V" band clamps
7-Housing base
8-Plastic cover
9-Center conductor
10-Center-conductor insulator
11-Output-signal cable connector
12-Tube insulator
13-Tube-insulating sleeve
14-High-voltage input
15-Spring-loaded capacitor connector

the center of the detector and a scintillator which is inside the photocell.

The photocell (Item 1 in Figs. C36 and C37) is an inside-out-type photocell with a 50-ohm configuration, constructed so that the scintillator can be inserted in the center. Therefore, the major portion of the emitted light from the scintillator passes through a transparent anode to the photocathode coated on the inside of the outer wall of the photocell. The photocell is capable of delivering a 30-amp linear output pulse into 50 ohms.

The scintillator (Item 2 in Fig. C37), which is inserted inside the photocell, is 3/4 in. in diameter and approximately 3 in. long. The small size of the scintillator simplifies the shielding required for radiation collimation.

One problem we now have is how to test the resolution of this equipment. We need an accelerator that will provide a burst of radiation of 1 roentgen in 1 mμsec into the scintillator. That is a radiation rate of 10^9 r per second. I understand that such accelerators are available, so that we may soon be able to completely evaluate this detector.

V. Recording System

Figure C38 shows the recording equipment. At the top of the rack are the trigger tapoff, the delay line, and the pulse inverter. The pulse inverter provides push-pull output at a 100-ohm impedance level, and has an input impedance of 50 ohms. The 100-ohm push-pull outputs provide push-pull deflection of the cathode-ray tubes. The pulse enters at the top of the rack, goes through the delay cable, and then feeds through each of the oscilloscopes to the signal terminations.

Two types of oscilloscopes are used in the system. The top oscilloscope is a sensitive oscilloscope, requiring 1 ma of signal current input for 1 trace width of deflection, and about 200 ma for full-scale deflection. The second oscilloscope, of medium sensitivity, requires 0.02 amp for full-scale deflection. The third oscilloscope is identical to the second and with attenuators in the signal lines can display up to a 30-amp signal input.

Thus, the system you see here is capable of displaying data from one detector, with a dy-

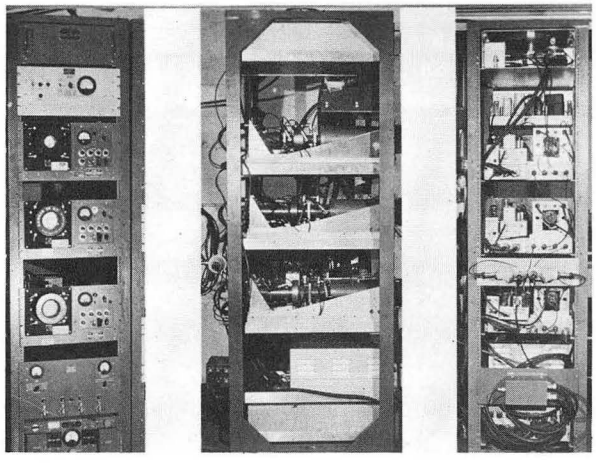


Fig. C38. Oscilloscope recording equipment.

namic range of 30,000 and with an accuracy of ±2% for the rise time of the phenomena being measured.

Figure C39 illustrates the principle of operation of the equipment; however, it does not illustrate the full capabilities of the equipment. The left-hand trace is a 0.5-mμsec linear sweep, with timing markers every 100 mμsec. The rise time displayed is about 20 mμsec. The right-hand trace displays the pulse as a Rossi trace, showing only the rise time of the pulse. The Rossi oscillator frequency is 300 Mc. The Rossi trace permits a very accurate measurement of the pulse rise time.

The oscilloscope traces displayed were from the medium-sensitivity oscilloscope. This oscilloscope is capable of displaying 1000 trace widths in a horizontal direction, and 600 trace widths in a vertical direction.

VI. System Discussion

Why do we require such a band width to perform measurements? This can be very simply illustrated by remembering that if you have a system that displays an output pulse rise time of 1 mμsec, the system is a 300-Mc system. If you utilize this same system and impress a 1-mμsec rise-time pulse into the system you will find that the output-pulse rise time is 40% greater. Even if the system were 1000 Mc, you would still have a 5% change in rise time. Therefore, if you really want to accurately measure the rise time of unknown pulses you need recording equipment that is 10 times as great in band width as the actual pulse you are trying to measure.

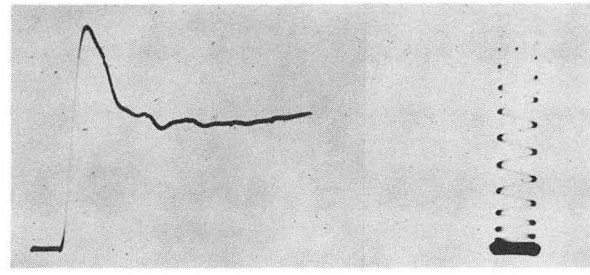


Fig. C39. Linear and Rossi traces.

An item which you may question is the decay time of the scintillator. The scintillator used has a decay time of 2.5 mμsec; however, the detector was originally designed to be a Čerenkov detector. Thus, with a distilled water radiator the transit-time limitations would be primarily those of the photocell, and you would then have a resolution of less than 0.3 mμsec.

Another item which may be questioned is the signal-cable distortion. This is the major limitation of the present system, since small-diameter cables attenuate and distort the signals. In some cases, we must use 3-in.-diameter transmission lines to transmit the signals from the detector to the recording station.

Two hundred years ago Ben Franklin was acquainted with millimicrosecond phenomena. Franklin did not realize that when lightning came down his kite string and jumped from the key to his knuckles, it took just about a millimicrosecond for the lightning to jump from the key to his knuckles. The rise time as measured by Ben Franklin's reaction was considerably slower than that which the equipment I have just discussed is capable of measuring.

VII. Future Improvements of the System

You may be interested in future improvements of the system. Mr. Goldberg, of EG&G, will present a paper on a cathode-ray tube with a band width of 4000 megacycles. This cathode-ray tube is being constructed to enable us to check the present system. A vacuum switch is also under construction which will have a rise time of 0.1 mμsec, capable of controlling 100 amp at 50 ohms impedance, thus producing a 5000-v output pulse. We will then be able to test the present equipment to see if there are any minor distortions in the system. Knowing the system's characteristics, we can calculate any minor distortions that might affect the signals being recorded. The present system is un-

der refinement so that it will have a band width of more than 1000 Mc, with a falloff of less than 1 db, or less than a 10% drop at the 1000-Mc point. Extraneous pulse reflections will be reduced to less than 1% in amplitude anywhere in the system.

VIII. Conclusion

The system that has been described has filled the need for a high-resolution wide-dynamic-range detection system. The detector design is compact and permits special collimated detector arrangements. The use of three oscilloscopes, the sensitivities of which can be varied, allows the coverage of a very wide dynamic range of the phenomenon observed by the detector.

The point I would like to leave is that if you really want accurate data concerning a phenomenon that you do not understand, you need equipment with band widths ten times as great as the phenomenon you are attempting to measure, to obtain reliable and significant results.

D-1. FAST-OSCILLOSCOPE REQUIREMENTS

Dick A. Mack

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Oscilloscopes have become such an important item, both for acquiring data and for testing the performance of an experiment, that it is worth while to list some of the desirable features and some of the objections of present high-time-resolution equipment.

In recent years oscilloscopes with attached cameras have fulfilled a dual function of allowing visual observation and providing a permanent photographic record. Both Polaroid and moving-film photography are used extensively interspersed with visual observations. It would be worth while for the manufacturers to think in terms of a compatible camera-and-scope unit in which a camera and viewing hood can be rapidly interchanged or perhaps used simultaneously. Present peepholes and viewing schemes leave something to be desired for observations at low light levels.

In a number of cases the vertical-deflection amplifier is bypassed and connections are made directly to the deflection plates of the cathode-ray tube. New instruments should be so designed as to allow easy access to the deflection plates through connections that do not degrade with the fastest signal components the CR tube can resolve.

Improvements could also be made in the manner in which the deflection plate leads are brought through the tube envelope. The ideal, of course, would be a system that presents a constant impedance to the input signal within the resolution time of the cathode-ray tube.

Another factor to consider is the interchangeability of multigun cathode-ray tubes. It would seem worth while for one to be able to interchange single-gun tubes with two-trace or perhaps even four-trace tubes without the necessity of rewiring the socket or replacing the deflection-plate leads.

Presently some manufacturers provide signal attenuators with their oscilloscopes. This has been most useful. It is important that in the future the attenuator also present a constant impedance throughout the band width of the CR tube.

As units with faster sweep speeds become available a line stretcher would be a useful adjunct. It should be suitable for mounting adjacent to the indicator unit for easy adjustment.

Another useful device in which there is interest is a constant-impedance switch. This would allow the observer to rapidly select one of several external inputs or the internal vertical amplifier.

A number of the above features would be useful in a proposed method for checking coincidence systems during the course of an experiment.

Figure D1 illustrates two common counting systems. Coincidences from the detectors are registered on scalers or photographs are made of the CR-tube traces. For an adequate test procedure an additional source of signals is needed whose amplitude, duration, and separation are known precisely. Electrical pulses could be injected into the system at points A and B or light pulses could excite the phototubes at points C and

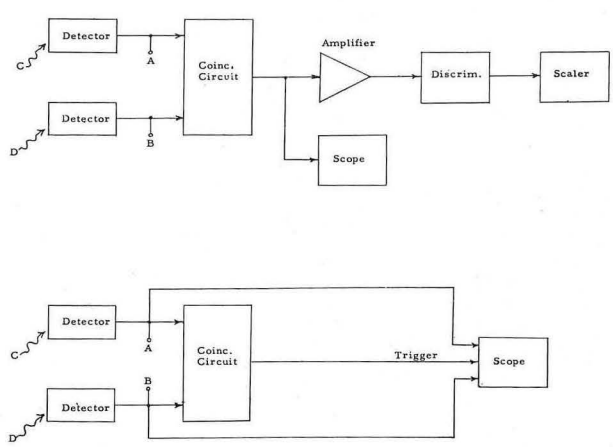

Fig. D1

D. For experiments on pulsed acceleration there is ample time between beam bursts to transmit test signals and evaluate system performance; for continuous sources, counting can be interrupted periodically for the test routine. To trace delay curves of the coincidence system one would electrically program a delay in one signal channel with respect to the other; to observe amplitude threshold levels, one would program the signal amplitude. The constant-impedance switch discussed above should electronically--or at least in a rapid mechanical fashion--switch to different parts of the system to allow observation of the system performance. Gatti (in Paper B-6) has made an additional improvement and fed the output of the test signal back into a correction circuit and thus kept the system aligned. The switch referred to above does not necessarily have to be built into an oscilloscope, but oscilloscope manufacturers could logically provide such units.

D-2. REQUIREMENTS ON FAST OSCILLOSCOPES

Quentin A. Kerns
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University of California, Berkeley, California

We all would like to see the oscilloscope switch that Dick mentioned.

An approach that we have used to a particular problem, that of switching between amplifier input and direct connection to CRT deflection plates, is shown in Fig. D2. This is a switch to carry signals through coaxial transmission lines to the junction at the deflection plates and back out. The ends of the transmission lines can be moved into three distinct positions. In the position shown, the deflection plates are connected to a pair of

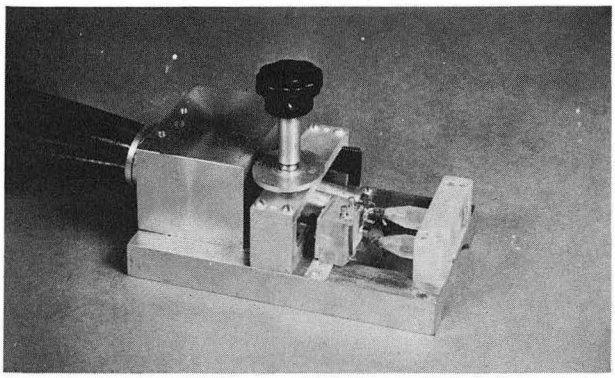


Fig. D2

joined 125-ohm lines. When the switch is moved to the second position, the CRT plates are connected to a pair of 50-ohm lines; and in the third position, the CRT plates are connected to the distributed amplifier in the oscilloscope.

The switch mounted at the side of the 5XP11 cathode-ray tube in the Tektronix 517 scope is shown in Fig. D3. At the rear you see the coaxial lines leading to the switch. The handle for the switch plugs in and extends slightly outside the instrument case; it has been removed for this photograph.

The decision to construct a switch was based on the following idea: It is an advantage to have direct connections to the CRT plates. At present, 1 mμsec rise time is available in the 5XP-type structure. However, distributed amplifiers are at present somewhat slower. One wishes to have a coaxial input available to take full advantage of the cathode-ray tube's rise time without making it difficult to use a distributed amplifier. In practice, the switch has been quite useful in giving this type of flexibility.

We may expect that, with future development, cathode-ray tubes of one-tenth of this rise time will be available, i.e., 10^{-10} sec. Distributed amplifiers, on the other hand, may perhaps be limited to 2 mμsec rise time. Here again a switching arrangement would facilitate the use of either the fast rise time of the direct connection, or the greater gain of the amplifier channel.

We find in our work, very often, that it is necessary to have perhaps three oscilloscopes to conduct one experiment. We may have small-amplitude pulses of some sort in the circuit. For these we must use amplifiers. Later on in the circuit we may have a signal of larger level for which it is necessary to look at the rise time accurately, so we switch to a different oscilloscope. Changing oscilloscopes is time-consuming — I hope that we will be able to do this within the oscilloscope itself in future commercial designs.

Let me draw a picture to illustrate a point in connection with triggering the oscilloscope sweep.

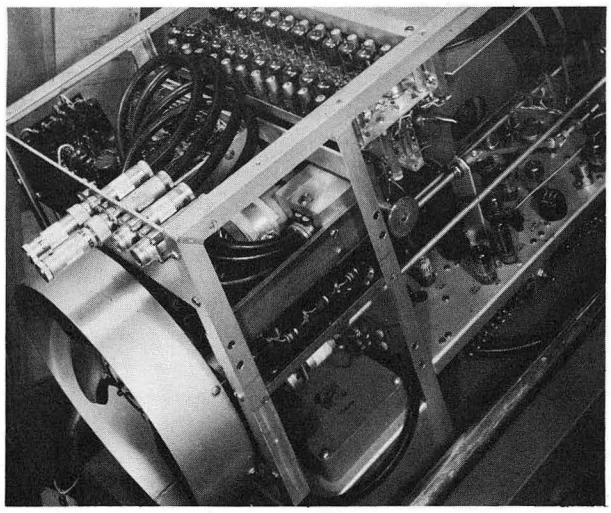


Fig. D3

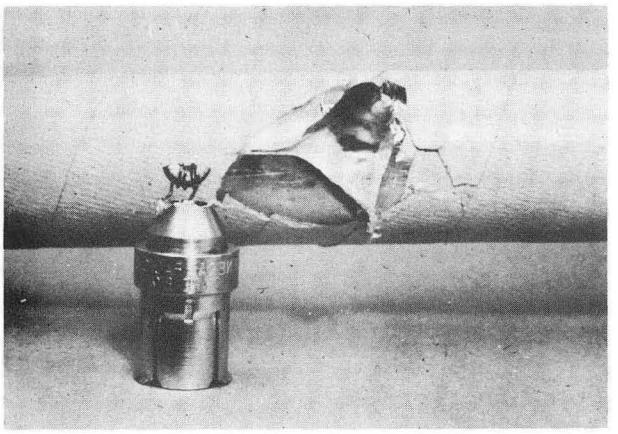


Fig. D4

The system of tapping onto the incoming transmission line with a resistor, in the case of the high-speed scope, causes an energy loss in the resistor which can be avoided. We have replaced the resistor with a small ferrite transformer core, or more accurately, a section of core wound with several turns of wire. The main coaxial line is maintained at very nearly constant impedance, while providing an output sufficient for a trigger. For example, a trigger signal that is 1/10 of the main signal is obtained with less than 1% reflection. Figure D4 shows the physical result of such an approach. This is an exploded view of a 125-ohm transmission line which we used for reflection testing. In order to evaluate the degree of mismatch that this pickoff introduced, we placed a 12-foot section of 125-ohm line in a typical reflection-test setup. That is, a fast-rising pulse is transmitted (in the reverse direction) through the vertical system of a traveling-wave deflecting scope and down the 125-ohm line to a terminating resistor. By use of several thousand volts pulse voltage, a few-percent reflection is rendered as full-scale deflection on the scope, and small perturbations are easy to evaluate. The two pieces of copper foil are lifted up here to show the hole in the styrofoam where this core was inserted. The section of ferrite core links part of the magnetic lines of flux around the center conductor.

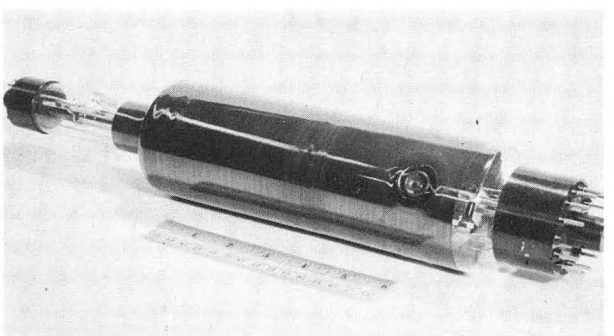


Fig. D5

I would like to make another remark on trigger circuits for oscilloscope sweeps: it would be an advantage to have a trigger circuit which has less amplitude sensitivity than present types, which tend to trigger sooner with large-amplitude signals and later with small-amplitude signals. The work of Professor Gatti, I believe, is apropos in this connection, for one would really like to have triggering delay based on something other than simply the time the pulse reaches a certain amplitude or rate of rise. Hopefully, one might ask for another position on the scope trigger switch to provide a time base starting from the centroid of an applied pulse.

We have done a certain amount of work with sampling oscilloscopes. In 1950 the Bevatron requirement for a frequency monitor led to the development of a tube which involved an electron gun, a set of deflection plates, and a small aperture ahead of a multiplier structure. (Fig. D5).

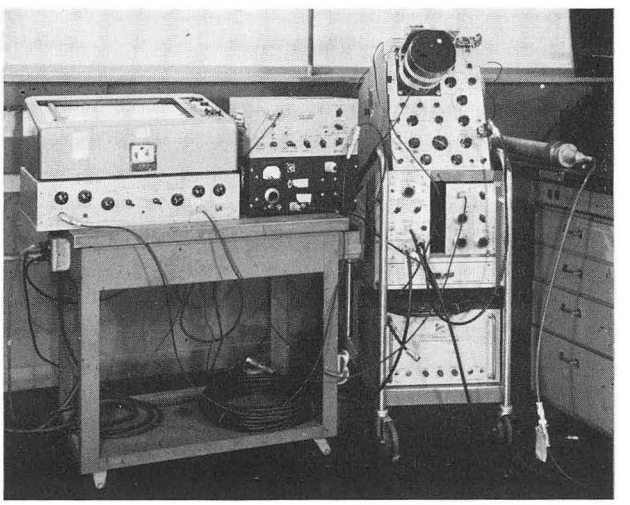


Fig. D6

This tube was used in a sampling oscilloscope, for low-amplitude pulse work, giving a rise time of about 2-1/2 mμsec, and a noise level a few times thermal noise. However, it had some features that were undesirable: it was very vibration-sensitive, and required extensive magnetic shielding to reproduce millivolt signals.

Another form of sampling scope is shown in Fig. D6. On the face of the cathode-ray tube there is a pair of slits, and within this black shield (one above the other) two photomultipliers whose

outputs, after a sweep passes the slit, are compared in a bridge circuit. The difference is used to control the vertical position of the scope trace, so that it passes, vertically centered, across the slit. In this cabinet there is a slow sweep generator which performs the function of moving the horizontal position of a repetitive pattern slowly past the slit. The vertical system meanwhile keeps the pattern centered. A plot of the vertical voltage required to do this and of a fraction of the horizontal voltage necessary to sweep the pattern is recorded as an x-y plot on chart paper. Figure D7 shows the attachment to the face of the CRT. These are the places where light enters the phototubes from above and below the trace. This taped slit on the tube is a few mils wide. There is a separator between the two phototubes so that light from an upper view of the trace enters the top tube, and from a lower view enters the lower tube.

The x-y recording does not affect the vertical-signal rise time, but it has saved us a great deal of time in presenting data; we plan to use more of such data readout in preference to stacks of photographs. We have taken many rolls of Polaroid film on cameras, and viewed the results on enlargers. Now, however, we also have accumulated many sheets of paper containing x-y plots from the sampling scope. The large plots are a convenient and useful way to keep data in the files, and permit us to make measurements more accurately than tracing from a small photograph, and more quickly.

Discussion

Roberts: Has any one been working on using traveling-wave amplifiers for a very-large-bandwidth oscilloscope?

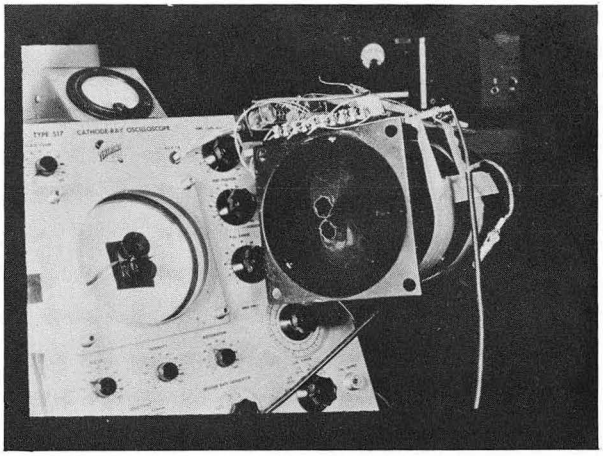


Fig. D7

Bell: Columbia has rebuilt Tektronix scopes with new distributed amplifiers, but these are not traveling-wave amplifiers!

Keuffel: I would just like to suggest that two things be incorporated if we do provide a coaxial direct connection to a scope, which has been suggested here: one, an attenuator, and two, some delay, built into the scope. These are the two items of flexibility that you lack when you go directly into the plates, and I think we all know this. But I think it should be written in the records that high bandpass, delay, and attenuators ought to be provided if the direct coaxial connections should be achieved.

Beckers: DuMont is making traveling-wave cathode-ray tubes.

D-3. THE DESIGN OF A HIGH-SPEED CATHODE-RAY TUBE WITH A DISTRIBUTED DEFLECTION SYSTEM

Jacob Goldberg
Edgerton, Germeshausen & Grier, Inc.
Boston, Massachusetts

Oscilloscope cathode-ray tubes are characterized by several performance properties. Among the important ones are sensibility (in volts per trace width), scan (in trace widths), writing speed (in trace widths per second), and band width.

These are familiar characteristics with distance normalized to the width of the trace. This is appropriate, since intelligence may be received only insofar as trace widths may be discerned.

In principle, it is possible to make any of these properties arbitrarily good; however, it will generally require a sacrifice of the others. Thus a problem in the design is to arrive at a compromise among all the useful properties in such a way that the tube has utility.

The tube's over-all capability should be systematically divided among all the desirable properties. It would be inefficient to obtain a high writing-speed capability if the frequency response were inadequate to faithfully present the high-speed phenomena which require it. Some sensitivity and resolution would have been sacrificed for this capability that would never be needed.

Figure D8 shows schematically the electron optics and trajectories typical of an oscilloscope cathode-ray tube. It essentially represents the conditions in the conventional, high-performance cathode-ray tube; however, these tubes have fundamental shortcomings which make them inadequate for the ultrashort pulse work presently being done.

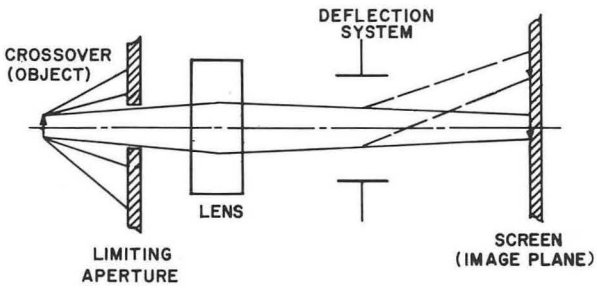


Fig. D8. Schematic representation of cathode-ray-tube electron optics.

A major failure comes about at high frequencies as the period or rise time becomes comparable to the transit time of the beam through the deflection system. The force experienced by an electron will then vary during its flight through the deflection system and the resultant deflection will be influenced by the rate of change of the signal. This degrades the fidelity of traces with high rates of change in amplitude just as effectively as do circuit properties.

To reduce this transit time, deflection systems have been shortened to the point where the cost in sensitivity, writing speed, scan, and resolution is great. At the same time, the need for high writing speed has increased in step with band width. Moreover, since there are no effective amplifiers with sufficient band width, there is an urgent need for good sensitivity.

Pierce proposed the use of a distributed deflection system to overcome the problems of long electron-transit times. According to this idea, the beam velocity and signal velocity parallel to the beam are matched by use of an appropriate transmission line as a deflection plate. This system has been so effective that with it we reckon band width in kilomegacycles rather than in hundreds of Mc, as in conventional systems. It has permitted the design of a tube that is better from the point of view of electron optics, thereby securing commensurate performance with respect to other properties. Commensurate performance now means very high writing speeds and a sensitivity that is still reasonable.

EG&G makes two different cathode-ray tubes with distributed traveling-wave-type deflection systems. They are designated the KR-1 and KR-3. Both produce narrow trace widths, and their various performance characteristics with distance normalized to trace width are quite high. The band width in both cases is about 2 kMc.

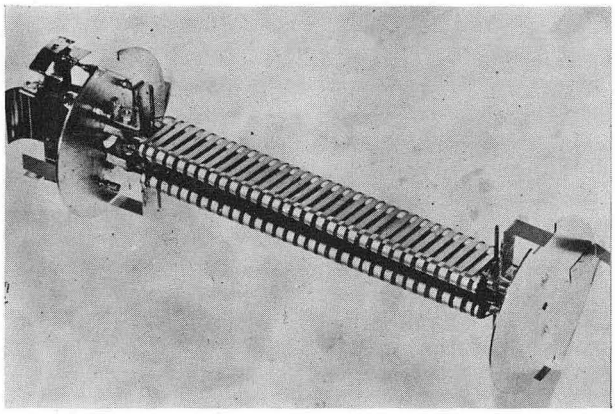


Fig. D9. Deflection system used in KR-3.

Figure D9 shows the deflection system used in the KR-3. The structure consists of a strip transmission line wound about a ground conductor in such a way that the signal advances along the axis with a velocity equal to the electron-beam velocity. The characteristic impedance of this deflection system, as well as that of the KR-1, is 100 ohms. They may be driven by balanced outputs of a pulse inverter driven at the 50-ohm level so that deflection is balanced, but with a reduction in band width.

The particular virtue of the KR-3 is very good sensitivity with high writing speed, while that of the KR-1 is a very great dynamic range or scan with high writing speed.

A third tube is presently under development and this is the main subject to be presented. The objectives for this tube are considerably greater band width and a writing speed to match. A trace width of 0.004 inch and scan of at least 250 trace widths are also specified.

The first need in this respect is the elimination of the pulse inverter which presently limits band width. Without the pulse inverter, balanced signal voltages will no longer be possible, therefore the tube must operate with single-ended deflection.

The second need is a reduction in impedance. This measure is necessitated by several factors.

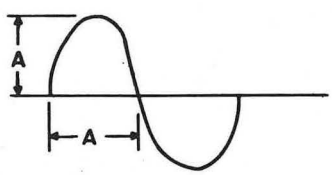
First, the design of the traveling-wave structure is made easier.

Second, the characteristics of transmission lines can, in general, be made better at lower characteristic impedance for the system.

Third, at higher impedance, the need for almost perfectly distributed transitions, connectors, and other transmission elements at frequencies within the desired band width would make the design a formidable task to accomplish. Moreover, to implement such a design into an actual physical structure without introducing unwanted stray capacitive loads does not seem practicable.

It should be realized that a stray capacity of about 0.4 $\mu\mu f$ is the most that could be tolerated at the 100-ohm level if a rise time of 10^{-10} sec is to be presented. This capacity can arise from something as slight as an isolated sphere of 0.030-in. diameter. At the 50-ohm level, there is a greater tolerance for these effects.

It will be shown that even in the design of this system with distributed deflection there is conflict between writing speed and band width. In anticipation of this condition and in keeping with the philosophy just presented, a standard will be adopted for a useful balance between the two. This standard is that writing speed and band width are commensurate if the intensity is just enough to record, on a single sweep, one complete cycle of a sine wave at the -3-db frequency with peak-to-peak amplitude and length of period each 200 trace widths. This relationship is illustrated in Fig. D10, which also gives expressions for the maximum spot velocity (or writing speed), derived on this basis.



$$W.S. = 6.6A\ f_{-3db} \times 10^{9}\ \frac{\text{TRACEWIDTHS}}{\text{SECOND}}$$

$$A = \text{AMPLITUDE}\ \left(\text{TRACEWIDTHS}\right)$$

$$f_{-3db} = \text{BANDWIDTH}\ \left(\frac{\text{KILOMEGACYCLES}}{\text{SECOND}}\right)$$

FOR A = 100 TRACEWIDTHS,

$$W.S. = 6.6 \times 10^{11}\ f_{-3db}\ \frac{\text{TRACEWIDTHS}}{\text{SECOND}}$$

$$\text{FOR } f_{-3db} = 5.0\ \frac{\text{KILOMEGACYCLES}}{\text{SECOND}}$$

$$W.S. = 3.5 \times 10^{12}\ \frac{\text{TRACEWIDTHS}}{\text{SECOND}}$$

Fig. D10. Relationships for writing speed.

For band width of 5 kMc the writing speed should be about 3.5×10^{12} trace widths per second. This is rather high performance, but is of the order desired. The writing speed is about 15% greater than the speed of light, based on a 0.1-mm trace width.

Securing this writing speed and scan without exceeding practical limits in sensitivity, aberrations, and accelerating voltage is a function of the electron optical design. These characteristics have been unified into the design method and it is possible to determine what measures will give this writing speed, with the specified scan and spot size and the best sensistivity.

For a constant spot size, writing speed is proportional to the beam power incident upon the screen. The voltages commonly used are already very high, so that an increase to even inconveniently high levels would not result in a very great increase in beam power. It would be much more convenient to rely on increased beam current.

There are two ways of increasing the beam current: first, by increasing the grid drive; and second, by enlarging the limiting aperture to accept more current. The maximum grid drive is limited by defocusing at high drives, therefore the remaining possibility lies in accepting a greater fraction of the total cathode current. This entails larger beam diameters and consequently greater aberrations, particularly those due to deflection. In fact, the current accepted is normally the maximum the electron optics will tolerate.

The design method considers the interrelation of accelerating voltage, beam current, beam diameter, scan, and deflection defocusing, and provides the following design equation:

$$W.S. = CV_B(V_B + V_{PA})\left(\frac{r_{tw}}{S^2_{tw}}\right)^2 \left\lfloor^2_{d_s^{1/2}} \frac{\text{trace widths}}{\text{second}},\right.$$

where C = a constant, characteristic of the screen, photographic process, and cathode loading,

V_B = voltage corresponding to the beam velocity in the deflection region,

V_{PA} = postdeflection accelerating voltage,

r_{tw} = tolerable elongation of the spot (measured in trace widths) due to deflection defocusing,

ds = trace width,

$\lfloor$ = length of deflection plate,

S_{tw} = scan (measured in trace widths).

In particular, this equation indicates distributions of accelerating voltage before and after deflection which will provide the required performance where the other parameters are given.

It is then necessary to select the distribution that gives the optimum total design with respect to any additional consideration that bears on the total problem, such as best sensitivity, economy of accelerating voltage, tube length, etc.

For this tube, it was decided that all the accelerating voltage would be applied as predeflection acceleration. The reasons for this are twofold: first, the greatest economy of accelerating voltage; and second, simplicity of construction owing to the elimination of a postdeflection acceleration system. This distribution is not the most efficient from the point of view of sensitivity; however, the sacrifice in sensitivity is not great. The voltage should be 20 to 25 kv for a writing speed in the range 3 to 3.5×10^{12} trace widths per second.

From this point the design of the tube with regard to placement of all the electrodes, apertures, focusing elements, etc., proceeds in a straightforward way and resembles the situation shown in Fig. D8. It is characteristic of this design that high currents and correspondingly large beam diameters--say, of the order of 0.3 inch--would be called for. Nevertheless, they are tolerable to the electron optics according to design criteria.

It should not be presumed that every step allowed by these criteria will be taken. The dimensions of the deflecting helix as dictated by band width impose certain restrictions to which the electron optical design cannot be adapted easily. Two of these are the maximum width of the helix and its separation from the opposing deflecting electrode.

The way in which the restrictions arise from band-width requirements will be briefly described.

If the effects of fringing fields are neglected, deflection sensitivity is reduced by 3 db at that frequency at which the signal shifts in phase by 2.82 radians during the time of flight of an electron along the deflection plate. For a helix like the one shown in Fig. D9, that frequency is the one at which the phase difference between the

voltages on two adjacent turns is 2.82 radians. By specification of the frequency at which this will occur, some of the dimensions of the helix are also specified according to the relationships given below.

The length of transmission line per turn corresponds to a transit angle of 2.8 radians, or

$$l_t = \frac{0.424}{\pi} \times \frac{1}{f_{-3db}} \text{ meters,}$$

where f_{-3db} = band width(in kMc).

The width of a wound deflecting helix like the one of Fig. D9 with the above length per turn has a limiting value of

$$W = \frac{0.212}{\pi} \times \frac{1}{f_{-3db}} \text{ meters,}$$

or one-half the length per turn. The actual width is somewhat less than this because of the effect of pitch and the small length of tape required to accomplish the bend at the edge of the helix. In large part, however, the maximum width of the helix is a function of nothing but the desired band width. The pitch follows from the beam velocity according to

$$P = v_B \times \frac{2.82\text{x}10^{-9}}{2\, f_{-3db}} = \sqrt{\frac{2e}{m} V_B}\ \frac{2.82\text{x}10^{-9}}{2\, f_{-3db}}$$

$$= 2.67\text{x}10^{-4} \sqrt{\frac{V_B}{f_{-3db}}} \text{ meters,}$$

where v_B = beam velocity and V_B = beam voltage.

The remaining details of the helix are the tape width and the ground-plane spacing, which depends on the impedance desired and the tape width.

For band widths of the order being considered, the length per turn is a little more than 1 in. This will provide a helix width of about 3/8 in. Since this is comparable to the beam diameter that would be called for, the deflecting field over the cross section of the beam will not be uniform. Unless small beam diameters are used and the deflection-plate spacing is kept small, severe aberrations of the spot are bound to occur with deflection. Furthermore, it is found in practice that fringing fields between turns act to reduce band widths considerably. A close spacing from helix to opposite electrode will also reduce these fringing fields and give a band width closer to the ideally computed value.

These limitations cannot be overcome easily, if at all, by electron optical design. If the deflection-plate spacing and width are restricted, the beam diameter that may be accepted, and hence the current, is also restricted. It appears that the writing speed that may be obtained will vary inversely with the square of frequency response (approximately), while the needed writing speed increases directly with the frequency response.

One may recognize four alternatives under this limitation:

1. Obtain a wide band width and reduce signal amplitude because of the lack of writing speed.
2. Maintain a balance between band width and writing speed according to the criterion initially presented.
3. Move the deflection system closer to the screen until the beam has converged enough to fit between the deflection plates (this will permit higher writing speed and greater band width at the expense of scan).
4. Employ a different type of distributed deflection system.

Any sacrifice of writing speed offers better sensitivity as compensation.

The final design is believed to be a balanced tube. The limits of scan extend to the limits at which deflection defocusing becomes excessive; enough writing speed is available to record the fastest phenomena to which the deflection system will respond faithfully. A substantial increase over existing band widths has been made. A different kind of distributed deflection system was devised. This one employs a zigzag transmission system, as shown in Fig. D11, rather than a modified wound helix.

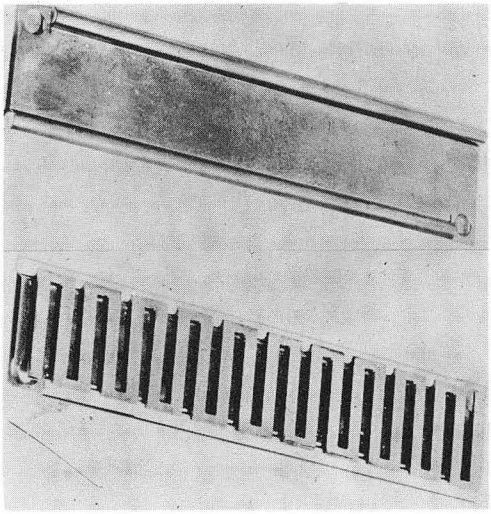


Fig. D11. Zigzag transmission system.

For this system the criterion for the -3-db frequency is the same. The difference is that the length of tape allowed is used entirely on the beam side rather than being about one-half expended on the back return loop. This permits the width of the deflection plate to be doubled for about the same band width.

Although fringing fields reduce band width, the greater ideally computed values practical with this deflector will provide greater actual values under the same conditions of fringing fields. It is apparent that this system eases the problem and permits a more favorable compromise between writing speed and band width.

The design that was evolved will give approximately the following performance:

Line width	0.004 in.
Band width	4.0 kMc
Writing speed*	3×10^{12} trace widths/second
Sensibility	0.44 v/trace width
Deflection factor	110 v/in.
Scan (signal)	2-1/4 in. (about 500 trace widths)
Scan (sweep)	2-1/2 in. (about 550 trace widths)

*Measured photographically with Royal-X Pan film at f/1.0 and 4:1 reduction.

In conclusion, some general comments about cathode-ray tubes should be given.

Reference is often made to the compromise involved in their design. This is certainly a correct reference. It implies that an advantage in any one area may reflect a universal improvement throughout the tube. Equally significant is the implication that, before any characteristic of value may be improved, one must usually be prepared to sacrifice some other valued characteristic or employ some novel, as yet unknown principle.

In a properly designed tube there are practical obstacles in three areas which limit the general performance. In principle, there is room for a lot of improvement in conversion efficiency at the screen, since at present it is only about 10% for the best screens.

The second area (and probably the greatest source of consternation to the designer) is the electron gun--the electron-source part of it. In present tubes, even where no thought at all is given to duty cycle, the highest cathode loadings rarely exceed 0.1 amp/cm^2. If the cathode's emission capabilities were the limiting factor, we should obtain about 100 times the usual loading and consequently 100 times the brightness on the face of the tube with no other costs. This in turn could be transformed to the improvement of most of the other characteristics. The failure at high loadings is attributed to space-charge repulsion among the electrons. This produces defocusing of the spot as the current density is increased. Diminishing returns rapidly set in, as the increased current to the screen is dissipated over a larger area and fails to materially increase the brightness of the spot.

The third area is in the photographic method. It is possible to show that there would be universal improvement in all characteristics if the spot size were reduced, provided that the trace width were used as the unit of distance. If a photo-optical system could be devised which for a reasonable cost would readily resolve 0.001 in. over a field of about 1 in. at an aperture not smaller than about f/1.0, this advantage could be exploited.

Over the last several years, film speeds have steadily increased. For many applications, this is just as valid an extension of performance as any advance made within the tube. It may be expected that future designs will be predicated on additional advances made by the film industry.

D-4. DEVELOPMENT OF A VERTICAL-DEFLECTION AMPLIFIER FOR FAST OSCILLOSCOPES

John Kobbe
Tektronix, Inc., Portland, Oregon

The development of an amplifier for the vertical deflection of an oscilloscope in the region of $\leqslant$ 5 mμsec presents many problems. In the medium-range amplifiers — 15- or 20-mμsec rise times — a straightforward amplifier system may be used, employing tubes with high G_m which basically have high input capacities, and cathode followers may be used to drive the high input capacity. There is a limit, however, to how far the use of cathode followers for isolating the output circuit from the input circuit of the next stage can be extended. For times of 5 mμsec or less other means must be considered.

The distributed amplifier is of course a logical thing to try. This device is not compatible with simplicity, however, and a lot of the amplified signals have to be absorbed in terminations and reverse terminations, lowering the gain of each stage.

Another approach is to reduce capacity to an absolute minimum and achieve high G_m. The high G_m and low input capacities are not basically compatible, as it is this capacity from grid to cathode that controls the current. A logical method might be to use a small input structure which has high G_m per milliampere and multiply the current in secondary multipliers.

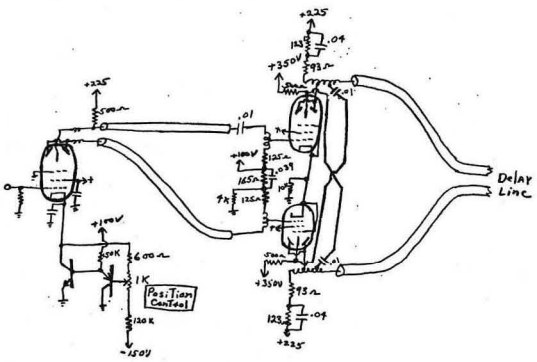


Fig. D12

Not having available the ultimate in multiplier vacuum tubes, but trying to select the best commercially available tube, we chose the EFP60. This multiplier type of tube has an advantage in that the output signal can be taken from both dynode and plate, and thereby a push-pull output is obtained, and one can obtain almost double the G_m.

In the arrangement shown in Fig. D12, the signal is applied between the grid and the cathode, and a push-pull output is taken from the dynode and plate. The dynode output is dc-coupled to the next stage with a low-frequency boost circuit of the same amplitude and time constant as the plate's ac-coupling circuit. The differential signal is in effect a dc-coupled signal.

The second stage is very similar except for being symmetrical and cross-coupled. The dc-coupling components still come from the dynode with a low-frequency boost to make up for the loss of dc and of low frequencies in the plate's ac-coupled signal.

The voltage gain of this amplifier, conservative with respect to the G_m expected from EFP 60's, should be about 15, but with most typical EFP60's we have tried, a voltage gain of about 20 to 25 was common.

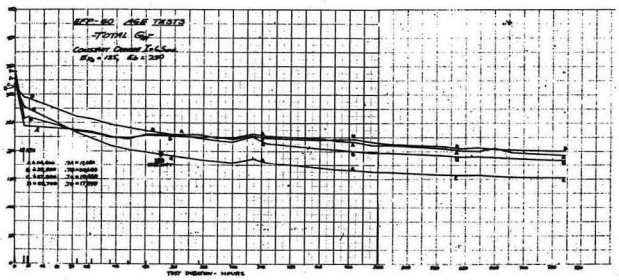


Fig. D13

Although this approach is basically satisfactory, the gain stability of the available secondary-emission tubes is not good, and for this reason we have not used it in a commercial instrument. Figure D13 shows the G_m fall-off of four individual EFP60's up to about 700 hours in a Class A operation similar to the operation in this amplifier.

The amplifier that was finally chosen for this commercial instrument is a neutralized distributed amplifier using frame-grid twin triodes.

D-5. TYPE-519 OSCILLOSCOPE

Clifford Moulton
Tektronix, Inc., Portland, Oregon

We have two reasons for coming here and talking with you. Of course one is to tell you about our products; the other is to determine ways of modifying or extending our present products and engineering aims to include wider applications.

Let us inspect Fig. D14, which shows some obvious triggering problems in the Tektronix 517. This problem is very likely "old hat" to many of you; however, to make the triggering problem very clear, we will use the 517 to demonstrate a basic trigger-system difficulty. The 517 is operating at 12 kv. The sweep timing has been dropped back to the next-to-fastest range. The 12 kv converts the sweep speed to 10 mμsec per cm. The rise time of the vertical amplifier is about 7 mμsec. The whole point of this illustration is that a reduction in the amplitude of this impulse-function signal produces a skewing in the time at which the wave form is displayed. Now if we were to connect a line between the tops of the wave forms it would show the locus of the skew error.

As for very fast oscilloscopes, the immediate problem is to make this skewing effect very much smaller. For instance, the scope we are now planning has a 1-mμsec/cm sweep rate and 6 cm of sweep length, so that the entire time of its scan is 6 mμsec. In Fig. D14 we see that if the signal were attenuated to half, the pulse would be skewed more than 6 mμsec, or completely off the screen of the faster oscilloscope. The point to leave with you is that triggering will be a very difficult job for any of us who pay particular attention to the shift of trigger time with pulse amplitude. We do plan to minimize the pulse-skew problem as far as practicable in the fast oscilloscope.

I have mentioned 6 cm sweep deflection and 2 cm vertical scan on the distributed-deflection or traveling-wave cathode-ray tube (there is some discussion on which of these two names fits the circumstances). We plan a linear calibrated push-pull sweep from 1 mμsec/cm through 2, 5, 10, 20, and to 1 μsec/cm for a total display length of 6 μsec, and we feel that this slow sweep will be useful for locating base lines or looking for low-frequency phenomena. Of the four commonly used transmission-line impedances, we have chosen the 125-ohm system. The reason for this is that we consider the oscilloscope a load impedance and we had best keep the load impedance high and not cause the source too much burden. Of course this also means that we have requirements for pads, attenuators, and matching components to facilitate matching to other common impedances.

We are expecting to make a system with approximately 1% voltage-reflection coefficient. The CRT is dc-coupled at 125 ohms and is single-ended. It has individual trimmers for each delay section in the distributed-deflection CRT. The number of trimmers is about 55, and we consider this the same as we consider tuning the delay line of an oscilloscope; by tuning this system we produce the optimum transient response. Rise time will be about 1/3 mμsec and response will extend to dc.

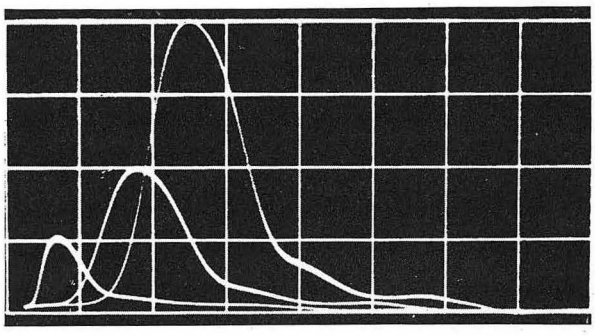


Fig. D14. Impulse signal to Tektronix 517 at 12 kv and 10 mμsec/cm sweep speed. Triple exposure shows skewing of sweep trigger time with input-signal amplitude.

The spot size we now plan is about 3 to 4 mils in diameter, and since this is a development situation, I'm sure I don't want to be held too close on numbers at this time. We have an internal delay line as a part of the oscilloscope package. The line itself is a 7/8-in.-diameter cable with 125-ohm surge impedance. While a customer's external transmission system might

well be other than 125 ohms, we chose to match the transmission system to the oscilloscope itself at the oscilloscope terminals, rather than to adapt the oscilloscope internal impedance structure to the requirements of each external system. So far as a vertical amplification system is concerned, we have nothing basically new to add to the vertical display problem. No doubt some applications will require vertical amplification, and we intend to supply some kind of vertical amplifier at a later date.

I want to be sure not to give the impression that this is a completed instrument. Let me assure you, however, that additional details will become available in the near future.

Discussion

(Question was on the sensitivity and resolution of the various recording devices that might be used, such as film, electronic, phosphors, and orthicon systems.)

Morton: I think that the order of sensitivity is: film is the lowest, the eye is next, and electronic devices can be made the highest. The quantum efficiency for a phosphor can be made 20 to 30% and for an electronic viewing device about 30%; for a film it would run about 0.1%. I think that that tells most of the story.

Bell: When you really wanted the fastest available writing speed wouldn't it be better to plan to view the oscilloscope with an orthicon?

Morton: I think it is possible to get down to the effect of each electron of your beam on the screen, certainly with some sort of electronic intensifier and perhaps with other means too.

Goldberg: I agree to the order stated with some reservations. If you use a very fast camera you will probably find you can see just about what you can photograph with Royal Pan. With Royal-X Pan, however, the advantage lies in film. This is our experience.

Winningstad: You have to take into account the human factor. The human eye is not really good enough for single transient work, and I presume that's what is under discussion, because your brain can't retain the information to get a quantitative measurement from the result. I've tried to measure fast rise times with small signals on traveling-wave deflection structures. You cannot remember the significance of the picture long enough to get a rise-time number out of it. You have to have it reproduced on graph paper or film or in some other way in order to be quantitative. To tell whether or not there is a signal there your eye is probably considerably better than film.

Jones: We have worried about this quite a bit. The number 2×10^8 quanta per square centimeter, the sensitivity of Royal X-Pan, has been pretty well verified. Qualitatively, in just trying to decide whether or not we saw a cosmic-ray track, we found that anything we could say we saw by eye we could photograph. The difference between some of the numbers that are quoted comes in the following way. If you know when and where something is going to occur you can detect it by eye, but if you have to examine your human memory and say Was there a cosmic ray? and Did it go this way? then I agree with you that film is much better probably—or at least it is equal. This is when you use a hand magnifier to look at it and an f/1 lens to photograph it.

Lynch: I would like to know if there is any serious work on using intensifiers after cathode-ray tubes.

Morton: It would not be necessary to use essentially a light amplifier. An image orthicon would give considerable additional speed.

Gatti: Sampling oscilloscopes have a definite advantage, as far as I know from the work at Harwell and Brookhaven, in sensitivity and in simplicity. But the major drawback is that they require repetitive pulses or at least the making of a selection of pulses of definite amplitude, as Sugarman made. An obvious idea should be to make a single pulse to be repetitive by feeding it into a low-loss delay line at one point at very high impedance--say, the plate of a pentode--and with nearly perfect matching, so that the pulse can go around and around, say a hundred times, without appreciable attenuation. With styrofoam cable this doesn't seem so impossible. You can pick up the signal to be sampled at the other diameter of your line, for example, with a double-grid tube. With this tube normally cut off, as this grid does not normally see electrons, it is not loaded for high frequency. And the signal can go round and round. It can, incidentally, be disturbed at the instant of sampling because there is a bunch of electrons flowing through this grid. But since each sample is of a slightly different part of the signal, if this line is not distortionless, this disturbance has no effect.

One has to try to kill the pulse after it has gone around a hundred times, or one lets it die if the repetition rate is not too high.

Wells: It seems to me that the input pulse doesn't know whether to go to the right or to the left and so it goes both ways, and you have really the equivalent of two cables in parallel. You really need only one cable--you don't need a circle at all.

Gatti: I think there is a definite advantage, because I have a lower impedance at the input and so the small lumped capacity at the plate of the tube will be shared by the two lines.

Wells: You could have three or four. You don't have to stay with a circle.

Maeder: Gatti's proposed arrangement of a closed cable loop, with only one tube feeding the input signal into the loop, appears to be equivalent to a single piece of cable left open at both ends. However, it seems to me that a truly circulating wave could be produced by feeding the input signal into the loop in a distributed-amplifier fashion. (See Fig. DA.) This arrangement would build

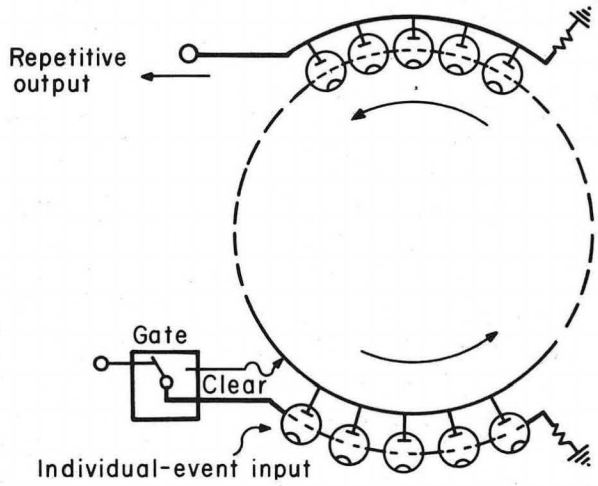


Fig. DA

up a large signal in the desired circulation sense. To destroy the stored wave, a small signal picked up from the cable at the proper phase and gated into the distributed-amplifier input would be sufficient.

Moulton: The trouble is that you would have to have another system to kill the back wave so that it wouldn't be seen by the detector, and when you do this I think it adds up to canceling the forward wave. Any way, what it amounts to is that the back wave is in the system as well as the additive time signal.

Maeder: But the contributions flowing in the wrong direction are not in proper phase relation to build up a duplicate of the fast input signal. Rather, they would sum up to small low-frequency background. If the pickup structure were also made in a distributed-amplifier fashion, we could discriminate also in the pickup process against the wave traveling in the wrong direction. This principle has been used successfully, in a different frequency range, for eliminating unwanted reflections in ultrasonic memory lines (D. Maeder, Helv. Phys. Acta 30, 347 (1957)).

Moulton: I want to comment about distributed amplifiers and terminations at the same time. Given a single-ended driving system, we must terminate the distributed grid lines at the far end because the reflection is not permitted to come back through and turn the tubes on again at a different time phase. Given a distributed-amplifier driver, we must terminate the back side of the distributed plate line. The energy traveling this way adds, but the tubes contribute a component which arrives out of time at this termination. It is then necessary to absorb the back-wave signal. Even though the back-wave components are out of phase they still must be taken into account.

Winningstad: I'd like to link this up with some comments that were made earlier. I think someone asked, "Has anyone used the traveling-wave-type amplifier, and presumably a carrier system or otherwise, to improve the vertical sensitivity of the oscilloscopes?" That, of course, is brought in here. One of the big troubles we have encountered is that people who make these devices seem to think that they're wide-band devices. They forget that the devices are in a hole, so far as low-frequency response is concerned, if one tries to use them directly. Therefore carrier-modulation schemes come up, and in general such schemes can be made to work. For example, the modulated 10-kMc carrier in a traveling-wave tube can be made to have a satisfactory 1- or 2-kMc band width. But the trouble is that the power levels the detectors can currently handle are not exactly suited to the direct-view type of oscilloscopes.

Lacy: The detector is certainly the key to using a traveling-wave-tube amplifier. Most people have used semiconductor diodes. This is the wrong thing--it is just out of their current-handling capabilities. There has been one proposal, by Mendel at Bell Labs, that looks quite satisfac-

tory. He uses a velocity-sorting detector in the output system, and this should be capable of handling many watts.

Goldberg (referring to cathode-ray tubes): We have worked out several designs with sensibilities going down to 2 mv per trace width. I don't know which one we will make, but we will make one with a sensibility between 2 and 30 mv per trace width.

D-6. FAST-RISE SAMPLING OSCILLOSCOPE AND PULSE GENERATOR*

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Presented by Robert M. Sugarman

Abstract

A simple and inexpensive sampling oscilloscope and mercury-switch pulse generator are described whose combined step-function rise time is 2.6 x 10^{-10} sec. The oscilloscope will display a 30-millivolt signal with negligible noise, and has a band pass from zero to 2000 Mc. The pulse generator is used both as a source of strobe pulses for the scope and as a signal generator for the circuit under test. The instrument may be used to display any wave form, synchronous with the mercury-switch pulse source.

Introduction

Pulse-generator testing of millimicrosecond circuits and associated components requires a test pulser and oscilloscope of submillimicrosecond response. The oscilloscope should also have a sweep speed sufficient to resolve these times to within a few percent, and a sensitivity adequate for the testing of these circuits at levels as low as a few tens of millivolts. The best commercially available pulse generators and distributed cathode-ray-tube oscilloscopes have combined rise times of about 4 x 10^{-10} sec, with sweep speeds unable to resolve these times to better than 20%. Sampling oscilloscopes are capable of the same performance and have greater sweep speeds and sensitivity,[1] yet do not have the extended band pass required to reduce the rise time below 4 x 10^{-10} sec.

The oscilloscope discussed here is essentially a mercury-switch pulse generator and a twofold coincidence system. A line stretcher is in series with one of the inputs to provide variable time delay, and a nonlinear element is used to detect the superposition of pulses. If both inputs of such a circuit are connected to the same pulse source, a plot of detector amplitude vs time delay gives a measure of the pulse width.

This measure may be made into a quantitative picture of the unknown pulse shape (see Fig. D15) by connecting one circuit input to a standard impulse derived from the pulser output, and the other input to the pulse of the unknown shape. Signal levels are then adjusted so that the standard impulse turns on the detector element, and the unknown pulse merely modulates this impulse. The detector output is then proportional to the instantaneous amplitude of the unknown pulse at strobe time plus a constant-amplitude switching pedestal. The signal display is obtained by connecting the amplified detector output to the vertical input of a conventional oscilloscope. One may provide horizontal deflection proportional

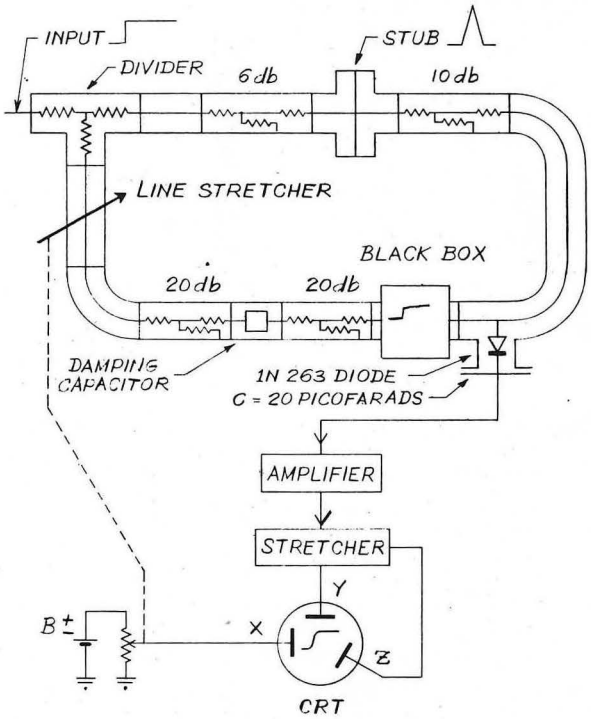

Fig. D15. Sampling oscilloscope. A 50-ohm system is shown with General Radio type-874 hardware and attenuators, except for the three-way divider (Microlab DP-3). Total length of flexible cable is 6 feet of RG-9A/U. The stubs and their lead-in cables are RG-58/U. The damping capacitor is a section of 7/8-in. air line with a ratio of inner to outer conductors of 3/2.

*This work was done under the auspices of the U.S. Atomic Energy Commission.

[1] R. Sugarman, Rev. Sci. Instr. 28, 933 (1957).

to the line-stretcher time delay by means of a potentiometer, as shown in Fig. D15.

The strobe pulse has an effective width of about 2×10^{-10} sec, as determined by the rise time of the instrument. It is mechanically inconvenient to generate such short pulse widths directly within the pulser. The latter is instead used to generate a step function. This is differentiated to form a standard impulse by a clipping stub. Such a technique has the further advantage that a step function is available as a signal source for the black box (Fig. D15) under test, since a greater variety of test wave forms can be generated (and more easily) from a step function than from an impulse.

Pulser Description

The pulser itself is of conventional design [2] (Fig. D16) except that the coaxial cavity housing

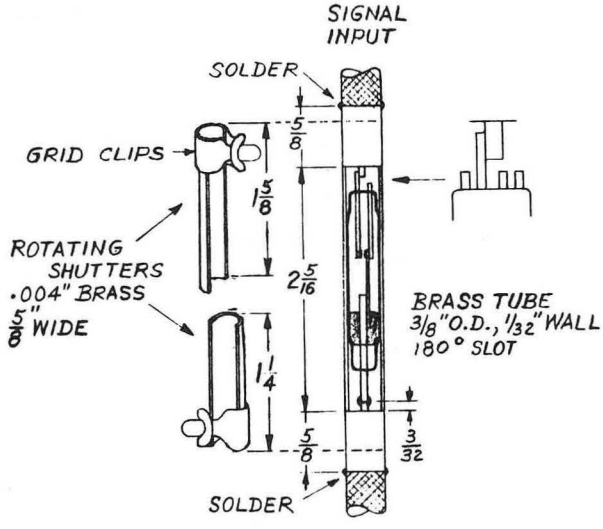

Fig. D16. Pulser subassembly. The switch is a W.E. or Clare 218-A (not all units of the latter have adequate amplitude stability). Coil is a Spencer-Kennedy A50313. Drive should be a sine wave or square wave at line frequency, variable in amplitude to 100 v, with a few ma of dc bias.

the switch is of adjustable impedance. This allows optimum empirical compensation for gross impedance discontinuities at the mercury well, auxiliary switch contacts, switch-to-cable transitions, etc. These adjustments may also be employed to adjust for optimum frequency response of the associated oscilloscope. For example, a rise time of 4×10^{-10} sec (see Fig. D18) without overshoot has been obtained by using this pulser with our sampling scope.[1]

[2] R. L. Garwin, Rev. Sci. Instr. *21*, 903 (1950).

The adjustable-impedance housing is a half-open tube which may be closed to any desired degree by rotating the two metal shutters, one covering the mercury well, the other the output section. RG-9A/U cable is inserted at each end of the tube except for its outer braid, which is cut back and soft-soldered in a butt joint to the tube. Three of the four switch output leads are cut to within 1/8 in. of the glass housing, the remaining lead to 3/16 in. The switch is then soft-soldered in the cavity, centered as carefully as possible. The cable ends should be clamped relative to each other at all times to prevent undue strain on the switch. A convenient clamping configuration is shown in Fig. D17. For most purposes the (partially open) center section may be left unshielded. If desired, however, a cylindrical shield may be wrapped over the assembly shown in Fig. D17. The pulse-forming line is charged at its remote end by a 50-K resistor. An oscilloscope synchronizing pulse is also taken from this end.

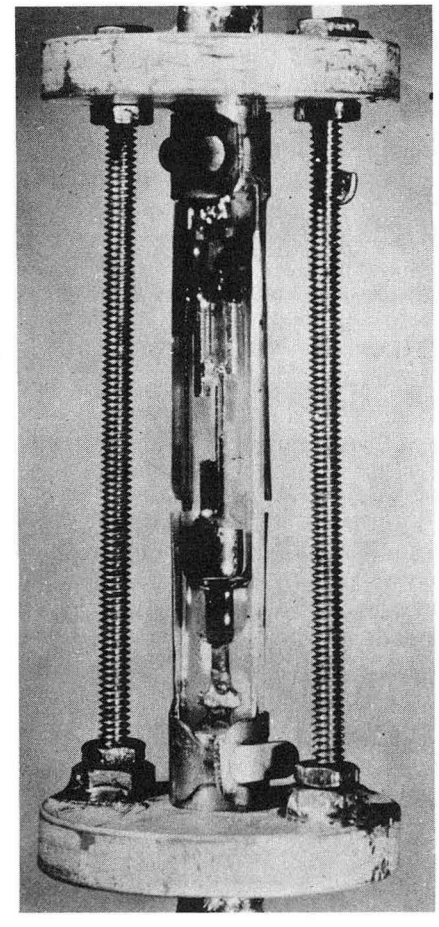

Fig. D17. Complete pulser. The end disks support the coil and an (optional) wraparound shield. To permit coil removal only one disk is soldered to the tube.

Oscilloscope Description

The pulser output goes to a three-way constant-impedance divider, labeled "input" in Fig. D15. One output of the divider goes to a 3/4-in. clipping stub which differentiates the leading edge to provide the strobe impulse. The input signal also passes through the line stretcher and attenuators to the device under test. A damping capacitor in the signal line reduces signal overshoot by a factor of two. The detector is a 1N263 diode mounted in a General Radio 874VQ cavity, the output capacity of which has been reduced to 20 $\mu\mu$f by mica spacers. The strobe pedestal pulse at the output capacitor has an exponential decay of about half a microsecond, and is adjusted to approximately 10 mv peak output by varying the potential of the pulser charging line (5 to 20 v). For 5% amplitude linearity the signal input must be attenuated so as not to exceed 30% modulation of the pedestal. The amplifier employed should have about 0.2 μsec rise time, reasonably low noise, an input capacity not exceeding 30 $\mu\mu$f, and a polarity-reversing switch or a bipolar output. Any signal sensitivity may be used. The limit is set only by the equivalent input noise of about 200 μv. Duration of the test signal is set by the length of the pulser charging line. The signal may, of course, be clipped by a shorted stub in parallel with the signal line. Exponential decays may be had by inserting a series capacity in the signal line.

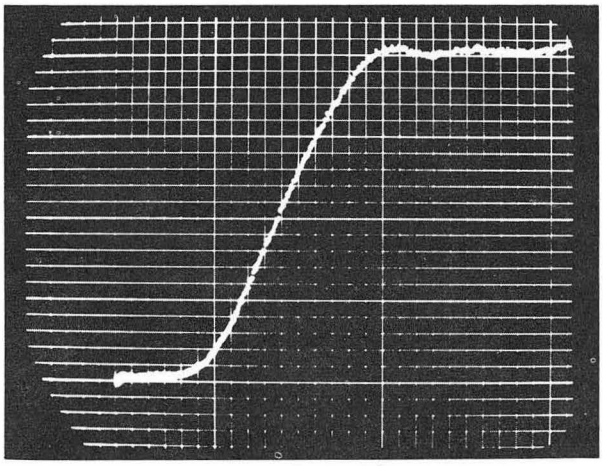

Fig. D18. Pulser response with the scope of Reference 1. Ten small divisions = 5.0×10^{-10} sec.

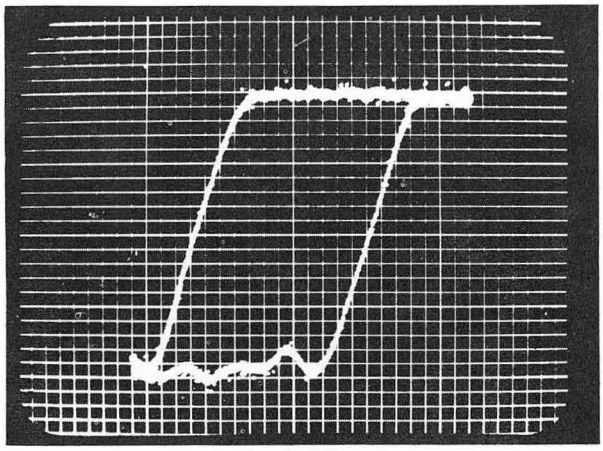

Fig. D19. Pulser-scope response. Time delay between wave forms is 6.6×10^{-10} sec; 10 to 90% rise time = 2.6×10^{-10} sec.

In its simplest form the scope may be used without automatic readout. The amplifier output is connected to an oscilloscope of good stability, the pedestal suppressed down screen, and peak pulse height plotted as a function of variable delay. A reasonable graph of the input wave form can be obtained in the time it takes to obtain a developed Polaroid picture of a scope trace.

For fully automatic display (Fig. D15) the delay line is driven through its range by hand or with a motor. Added visual contrast may be obtained by employing a pulse stretcher following the amplifier so as to show only the peak of each detector output pulse. The photographs of Fig. D18 and D19 were taken with both a motor drive and a stretcher. A single trombone General Radio LT line stretcher provides 1.3×10^{-9} sec delay, equal to five times the rise time, which can be extended by addition of fixed delays.

The test-pulse polarity may be changed by reversing the diode and the charging-line potential (together with the amplifier polarity selector if it cannot handle a bipolar output).

Performance and Applications

The pulser rise time is shown in Fig. D18 for the scope of Reference 1, and in Fig. D19 for the instrument here described. Six mercury-switch capsules all gave the same performance, although each required slightly different shutter settings.

The optimum shutter setting depends critically on the viewing system employed. With the scope of Reference 1 and 44 feet of RG-17/U cable delay, closing the bottom shutter effectively compensates for the rise-time loss characteristic of the delay cable. This compensating overshoot thus obtained is the result of increasing the capacity to ground of the mercury well in the charge line. Putting the mercury well in the output section grossly slows the rise time, since the (capac-

itive) mercury well is now across the signal output.

The top shutter has almost no effect on the scope of Reference 1. It is fairly critical in this 2000-Mc system with the damping capacitor, and extremely critical without it.

The pulser-scope frequency response is shown in Fig. D20, together with that of the scope of Reference 1. The fine-structure variations in frequency response are real and are caused by residual stub reflections in the system. Increase in the attenuation surrounding the stubs does reduce these variations, but has no observable effect on the rise time or overshoot.

The pulser-scope might prove convenient in the testing of multiplier phototubes, since a light flash of short duration[3] is available from the switch on contact closure.

[3]Q. A. Kerns, F. A. Kirsten, and G. C. Cox, Rev. Sci. Instr. *30*, 31 (1959).

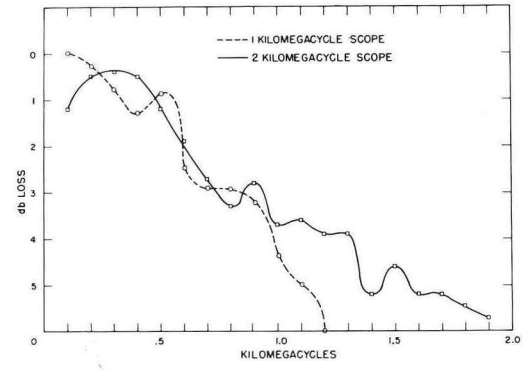

Fig. D20. Frequency response of pulser-scope. The frequency response of the Reference 1 scope is shown for comparison. Amplitude is measured as the peak random modulation of the strobe pulse by a CW signal.

Acknowledgment

The authors wish to thank W. A. Higinbotham for his advice, encouragement, and support.

D-7. SAMPLING OSCILLOSCOPES

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Hewlett-Packard, Inc., Palo Alto, California

We became interested in sampling scopes, actually, from the work by Dr. Sugarman, and also by Chapman at Harwell. We have been cautioned that they may not be too useful in the nuclear field, but apparently they have been of some value to the men mentioned above, who are both doing laboratory work in this field. First, I might say we are not too far into this so we can't give any too definite numbers, but I would like to compare some of the things we think are important in this system with the direct-display tube such as the EG&G scope or the one that Moulton has already described.

First we think of fundamental advantages in sensitivity. I believe the best numbers that have been mentioned on the distributed tubes are 30 mv per trace width, or sensibility of 30 mv. With this system we should perhaps compare a typical noise level. Doing this, we might have a noise limitation of less than a millivolt, which would mean a sensitivity improvement of 30 times or so, and of course the display is a little different; we can allow practically any size display for direct viewing.

Another advantage is in writing rate, since in the sampling scope the beam is always writing. There is no loss of intensity as you go to low-duty-cycle displays, and this of course is an advantage in the large direct-viewing tube, but is less important in the photographic setup. Another possibility with the sampling scope is a direct recording on an x-y plotter, which has been mentioned as being desirable. The sampling system is inherently well adapted to provide this.

Also in keeping with the general-purpose scope concept, it is possible to have a high-impedance input rather than a transmission-line input. Actually the heart of the sampling scope is contained in just a few elements, which determine the fast circuitry, and these you can just as well take to the thing you are measuring as bring the signal to them, so that it is possible to make a high-impedance input similar to what you would have in conventional slower scopes.

An advantage from the manufacturer's standpoint is that the sampling scope can be made largely from available and conventional components. Aside from the fast circuitry and the sampling circuit all the rest of the scope, including the CRT, is composed of ordinary items. We don't actually know just what is most desirable to use in the sampling circuit; we are at present trying to use semiconductors. In terms of disadvantages it is of course necessary to have a repetitive signal unless one can apply the idea mentioned by Dr. Gatti. The other principal disadvantage is the limited repetition rate that the circuit can handle. When the input is not terminated one must also be careful about reaction on the circuit under test.

D-8. PULSE GENERATORS

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Lawrence Radiation Laboratory
University of California, Berkeley, California

I will first describe a light source that promises to be of value not only for setting up but also for monitoring the performance of phototubes in coincidence circuits. In common with the p-n junction source described by Dr. Whetstone, this source emits light when subjected to high-voltage pulses. The amplitude of the pulses is stable, the time jitter between the electrical pulses and the light pulse appears to be less than 10^{-10} sec, and the light pulses are short, i.e., several millimicroseconds in duration. Measurements of the pulse shape and duration have not yet been made.

The light-generating mechanism consists of a small tungsten wire (3-mil diam.) whose point rests against a glass surface in an atmosphere of hydrogen at a pressure of about 14 psia. The generation of light is initiated when a high gradient is set up at the point of the wire by impressing a high-voltage pulse between the wire and the near-by metal parts.

Two models of this light source are shown in Fig. D21. The upper is the original model, designed for use in a pressurized gas Čerenkov counter. The light is emitted through the glass window on the right. The electrical pulse is introduced through the type-N fitting on the left. The newer model, below, is designed to be placed in various housings to meet the conditions of the experimental setup. Only one lead is brought out; the return path for the pulse is supplied by the housing.

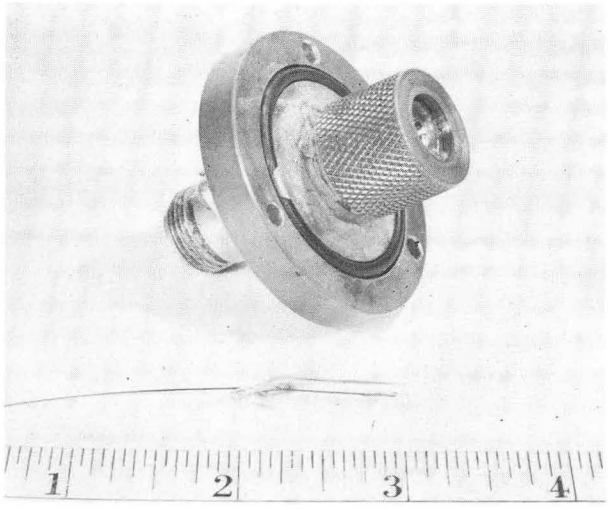

Fig. D21

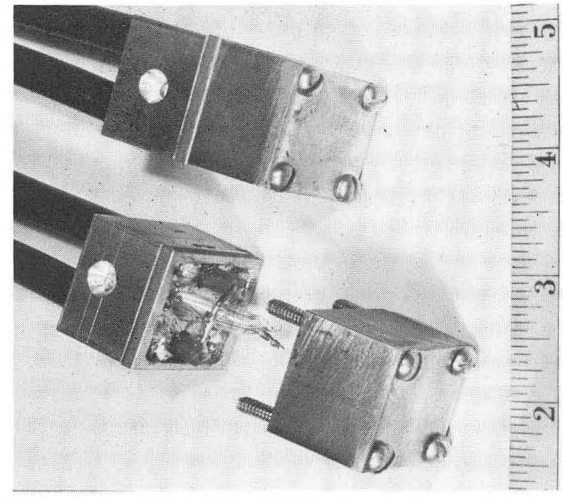

Fig. D22

Figure D22 shows two housings designed to be mounted alongside solid scintillators. Since the light pulser absorbs only a small amount of energy from the electrical pulse, several of these may be operated in cascade from the same electrical pulse generator. This permits the checking of coincidence circuits in situ, even though the counters may be physically removed from each other and without access to a common light source.

The power supply, shown in Fig. D23, uses four transistors, a large number of diodes in a Cockcroft-Walton circuit, and a mercury relay capsule to generate the hv pulses.

The pulse generated by the power supply and fed to the light source is shown in Fig. D24. Pulse amplitude is about 2800 v between the base line and the peak. The horizontal sweep speed is 1 mμsec/cm. Peak power is on the order of 100 kw in a 50-ohm line, but the average power is only a few milliwatts, since the pulse-repetition rate is about 100/sec. With this pulse generator, the light source gives pulses from the output of the

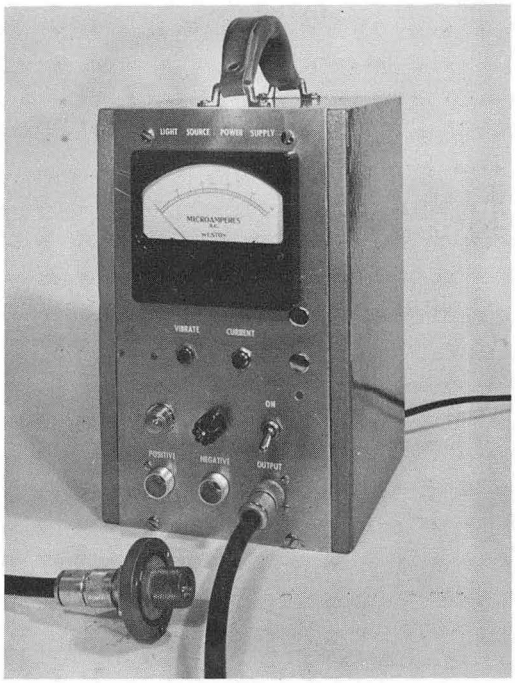

Fig. D23

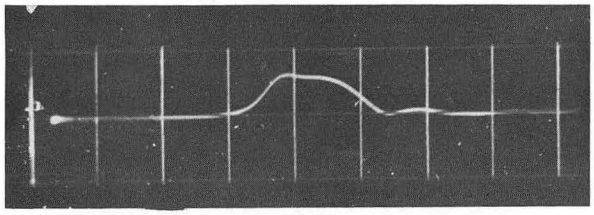

Fig. D24

usual 6810A phototube arrangement which look very similar, if details are ignored, to the pulses from a classic scintillator.

Incidentally, the oscilloscope that reproduced the pulse of Fig. D24 has been quite a workhorse in the group. It was the subject of an article in the Review of Scientific Instruments, July 1958, titled "A Fractional Millimicrosecond Oscilloscope System Utilizing Commercially Available Components." This oscilloscope has been responsible for a great deal of the test work that we have done with short pulses.

Figure D25 is included merely as a matter of interest. It shows a delay box containing 550 mμsec (a little over 500 feet) of styrofoam delay line. The delay line is built in sections that can be connected together to make an appropriate total length for an experiment. Figure D26 shows the pulse of Fig. D25 after it has gone through 300 mμsec of the styrofoam line. The sweep time is still 1 mμsec per centimeter.

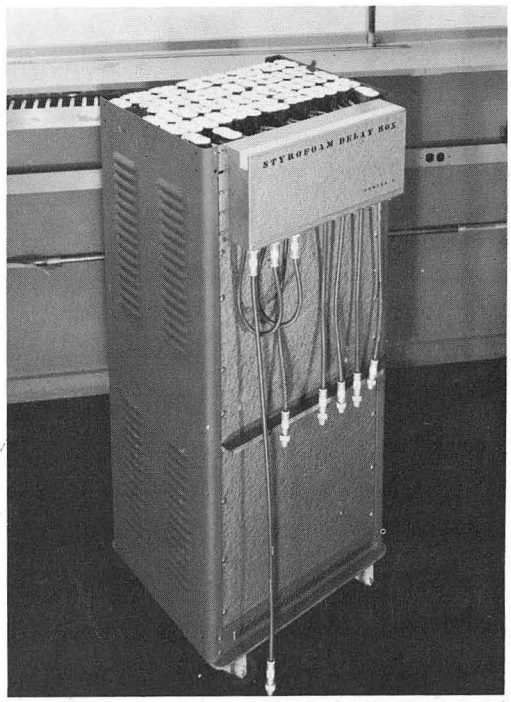

Fig. D25

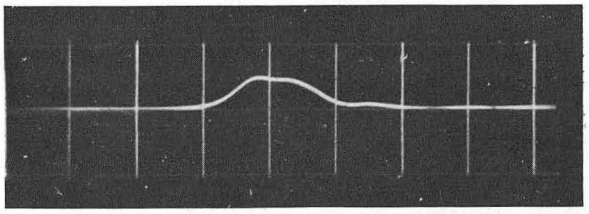

Fig. D26

The pulse transformer shown in Fig. D27 is used in a system that we are developing to make fast pulses. It has a 125-ohm input and a 10-ohm output consisting of five 51-ohm lines in parallel. The transformer is a rolled-up, tapered-

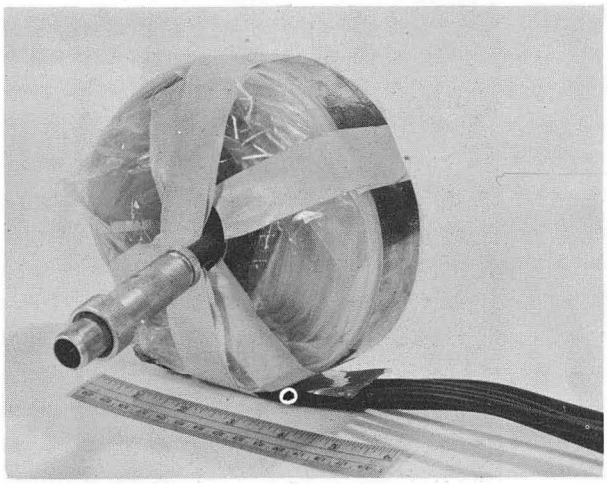

Fig. D27

line transmission line. The center conductor is a 10-mil-thick strip of copper, whose width varies from one end to the other. It is separated from a pair of constant-width ground planes by polyethylene of varying thickness, which tapers approximately exponentially from the thick 125-ohm end to the thin 10-ohm end.

In Fig. D28 the response of the transformer to a pulse from a mercury pulse generator is shown. The sweep speed is 10 mμsec/cm. It is interesting that the dc response of the transformer is quite good. That is, if you use the sharp edge in exceeding some voltage threshold, you have a dc response in completely saturated circuits following. It is for this purpose that we use the transformer.

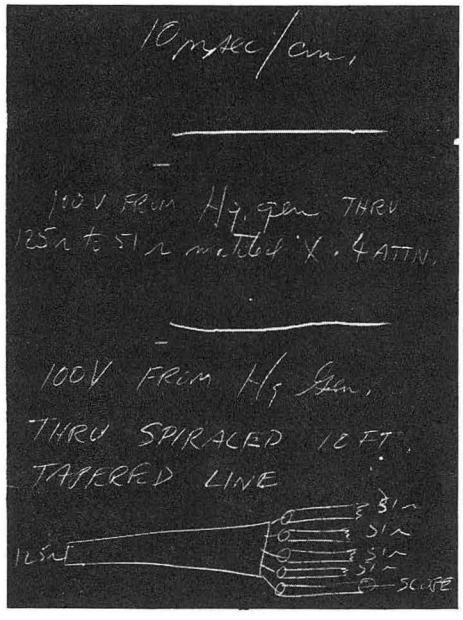

Fig. D28

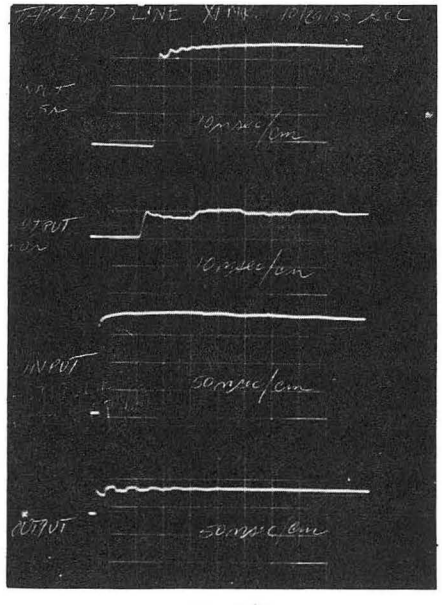

Fig. D29

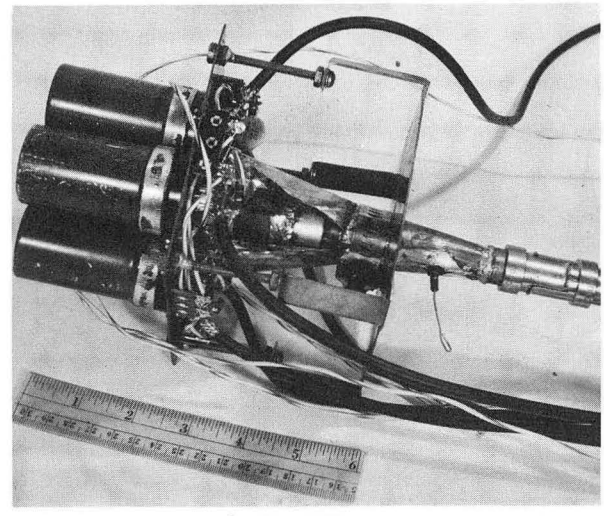

Fig. D30

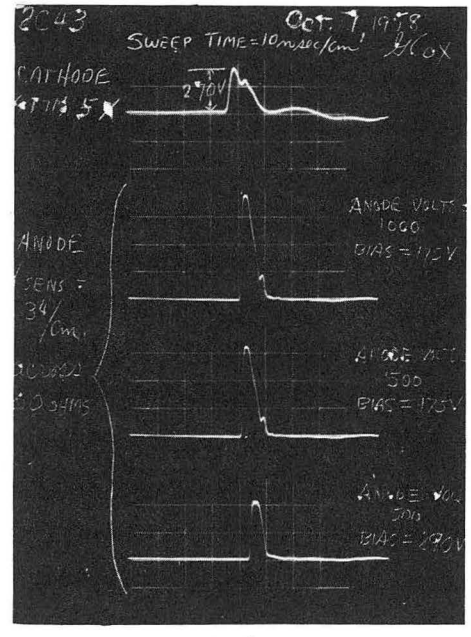

Fig. D31

The transformer is driven from the plate of an EFP60 in Fig. D29. The steps are reflections due to imperfect matching of input and output impedance. The output shown is typical for all five output lines.

Figure D30 takes us on to another part of the circuit. The five output pulses go to the grids of five EFP60 tubes whose anodes form a line of

approximately 20 ohms impedance going to the cathode of a 2C43 lighthouse tube. The 2C43 is partly visible in the line about 2 in. to the right of the bases of the EFP60 tubes. The grid of the 2C43 is grounded and the anode is connected crudely to a 50-ohm output line. What we hope to do is pulse the lighthouse tube into conduction by applying a negative pulse to the cathode.

Some of the pulses from the lighthouse tube are shown in Fig. D31. The vertical scale is 34 v/cm. The anode pulses are several amperes in a 50-ohm line. Notice that the timing of the vertical rise in the last trace has shifted to the right owing to change of bias on the tube. This illustrates that the portions of the pulse on the cathode that are below the threshold of tube conduction are not appreciably coupled into the anode circuit. Hence the current can rise to a sufficient rate in the slower circuits so as to bring the tube into conduction at a good rate of rise in terms of v/sec. The output pulse displayed on the previously mentioned fast oscilloscope is shown in Fig. D32. The length of the pulse is

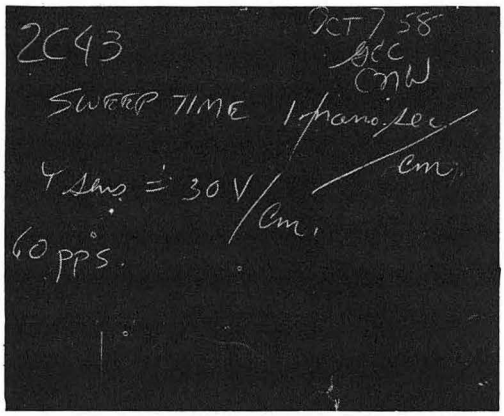

Fig. D32

not important here. We have shortened the pulse in some cases so that we can run at a repetition rate of 10 kc. The purpose of all this--and I hasten to state that we haven't completed the project--is to pulse some oscillators. Figure D33 shows a type of oscillator we have used in this work. This model is designed to operate at about 50 Mc. The schematic of the oscillator, which uses a grounded-grid triode, is in Fig. D34. Stray capacity and the large coil make up the resonant circuit. The coil is made of copper tubing so that the trigger signal can go coaxially through the coil and appear at the cathode. The trigger is negative so that the plate current, if the tube does not oscillate, follows approximately the voltage pulse fed in.

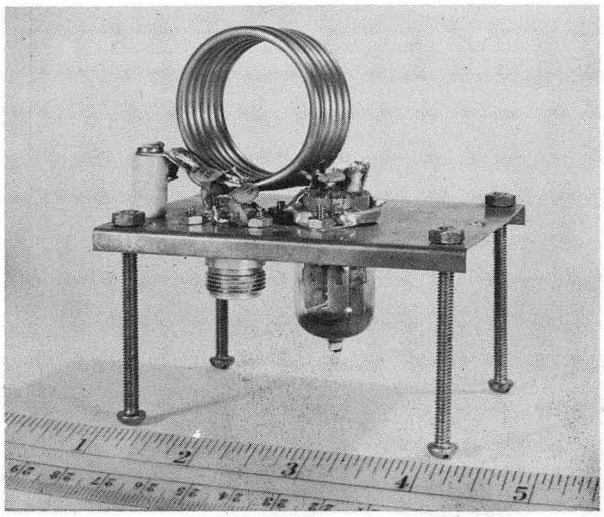

Fig. D33

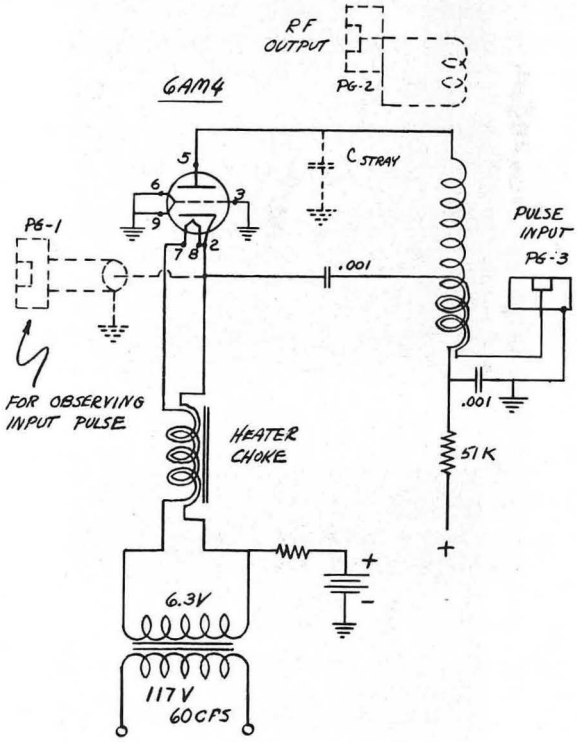

Fig. D34. Pulsed oscillator.

An oscillator for 540 Mc is shown in Fig. D35. Again we have a similar tube. Linear transmission lines form the resonant anode and cathode circuits. The filaments are brought out coaxially inside the cathode line. Coupling is by means of a small strap, shown directly above the tube in the picture, which provides a slight capacitance from the cathode line to the anode line.

The trigger goes in through the coaxial line at the right in the picture and rf comes out through the coaxial line at the left.

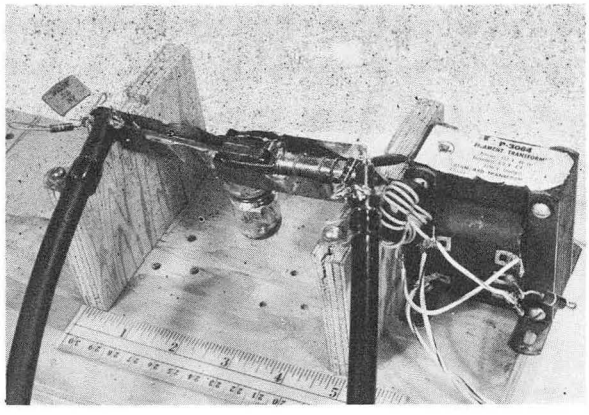

Fig. D35

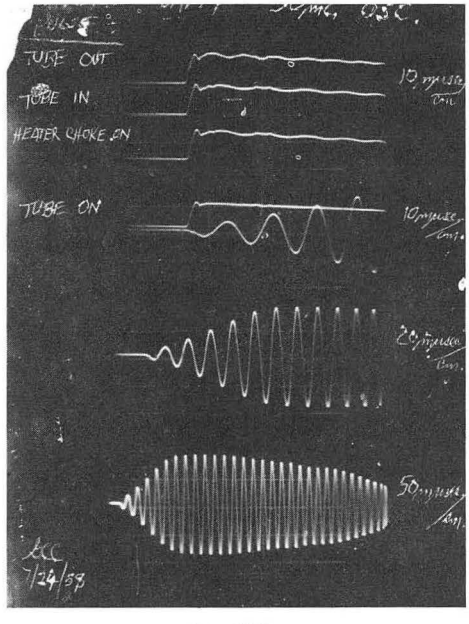

Fig. D36

Figure D36 shows some of the results of pulsing the 50-Mc oscillator. The top four traces show the wave form at the cathode observed when a pulse from a mercury-capsule electrical pulser is introduced at PG-1. The conditions under which the pictures were made are listed at the left of the photograph. The fourth trace, "tube on," was made with the resonant circuit disabled so that oscillations could not build up. The three lower wave forms show the output (PG-2) of the oscillator as observed at three different sweep speeds listed on the right.

The object of Fig. D36 is to illustrate that an oscillator can be pulsed on with reasonable rates of rise of the envelope. I would say, in general, the rate of rise may be approximately on the order of the RC time constant in an equivalent LC resonant circuit. The C represents the total shunt capacity in the oscillating circuit and the shunt R corresponds to the parallel result of losses (which may be small) and the negative resistance introduced by the tube in the feedback. Rise times on the order of 10^{-8} sec are certainly feasible provided the tank circuit capacitance is kept in the range of stray capacities.

Preliminary results of work in Fourier synthesis of a step function by appropriate pulsing on of these oscillators are illustrated in Fig. D37. We have added the outputs from pulsed oscillators that have frequencies of 180 Mc and 540 Mc and whose amplitudes build up in approximately the same way. The result is an approximate synthesis of a square wave made by adding

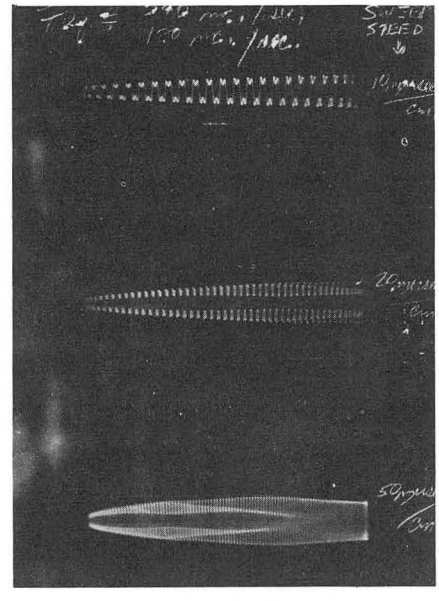

Fig. D37

the fundamental and third harmonic in the proper manner. The phase has been adjusted by setting the relative trigger-pulse delay for an optimum picture on the scope. The next step in the synthesis is, of course, to use more oscillators and arrange things in a useful, compact package.

One reason why we feel there may be possibilities for this method is that the starting time of the oscillator can be kept to a fairly small jitter. This is done simply by putting enough energy into the resonant circuit to exceed by a fairly large factor the thermal noise energy, KT, and noise contributions from the tube. Once the circuit has started to ring it is essentially incon-

sequential how you bring the tube into conduction, provided the method of doing so does not in itself introduce any transients that add energy to the tank circuit at its fundamental frequency. To summarize, then, it is possible to shock-excite a tank-circuit unit with a very short trigger pulse, of amplitude perhaps a thousand times the thermal noise level. Oscillations are thereby set up which begin to decay on the tank-circuit time constant. Plate current is then turned on relatively slowly. The result is a large-amplitude rf signal whose phase is determined at the beginning by the time of arrival of the trigger pulse. The

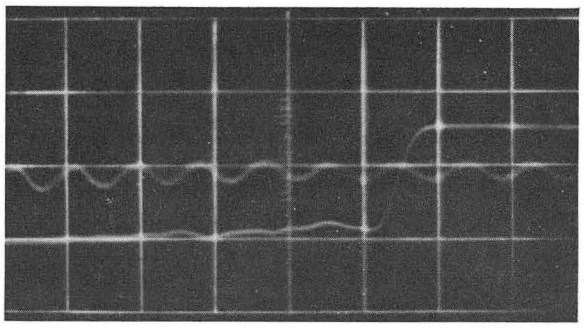

Fig. D38

traces in Figs. D36 and D37 were photographed with a 1-sec exposure and a pulse-repetition rate of 60 cycles. The jitter in phase is too small to detect at this sweep speed. Figure D38 shows a similarly made photograph of a pulsed 1000-Mc oscillator, and again the time jitter is very small.

Figure D37 was photographed on a Tektronix 517 with direct connections to the 5XP-CRT. I am sure that that wave form would appear quite different if viewed on a scope of sufficient band width for displaying it with small distortion. The phase of the third harmonic would be shifted and its amplitude probably would appear larger. We simply adjusted amplitude and phase until the picture on the scope looked reasonable. This brings out an important point: With the method of Fourier synthesis it becomes possible to correct for some types of distortion--for example, in the viewing equipment (cables, scopes, etc.). One could synthesize a pulse at Point A, transmit it through a cable having attenuation and dispersion, and still have the pulse appear at a Point B as, e.g., a step function. It appears that this can be achieved provided the desired form of the output pulse is realizable within the constraints of our ability to adjust the phases and amplitudes of the initial component parts of the pulse. In cases in which one would like to see the shape of a pulse response from some device without having to correct for cable distortions and so on, this feature would be extremely helpful.

In the Lawrence Radiation Laboratory Counting Handbook there is a section (CC8-20) on the gating of multiplier phototubes. This technique has application in the generation of electrical pulses. The pulse in Fig. D39 is from the anode of a 1P21 multiplier phototube operating with the voltages indicated in Fig. D40. The peak amplitude is about 1 amp. The light source was a small incandescent panel lamp arranged so as to produce a continuous photocathode current of perhaps 0.1 ma. The voltages on the dynodes were adjusted so that Dynodes 1, 3, and 5 were out of their normal operating positions in the voltage divider. This

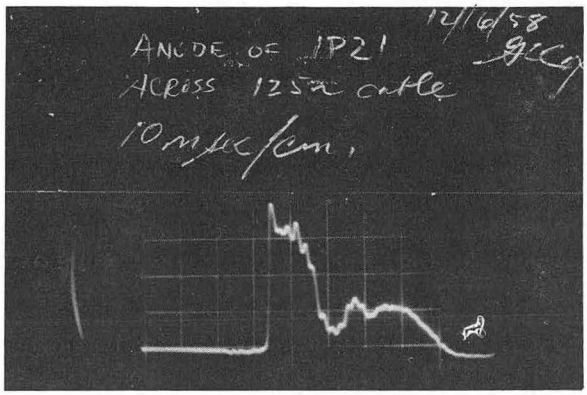

Fig. D39

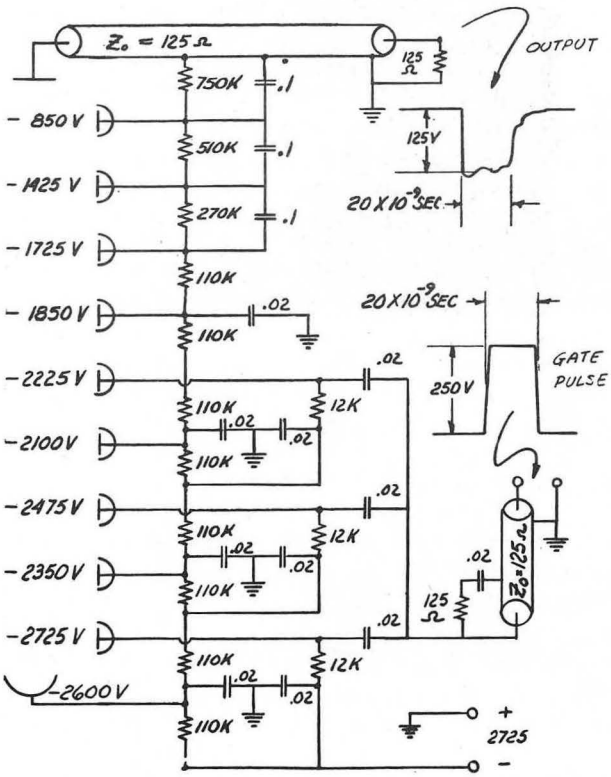

Fig. D40. Gated IP21 multiplier phototube.

made the tube gain relatively low. In making the picture, we attempted to apply a flat-topped gating pulse of about 10-mμsec duration to Dynodes 1, 3, and 5 so as to bring the gain up to precisely its normal value for the duration of the gating pulse. We discovered, of course, the usual ringing and overshoots one encounters in trying to introduce fast pulses into tubes. Figure D41 shows the results of reducing these effects. For this picture, we also lengthened the gating pulse to 1 μsec.

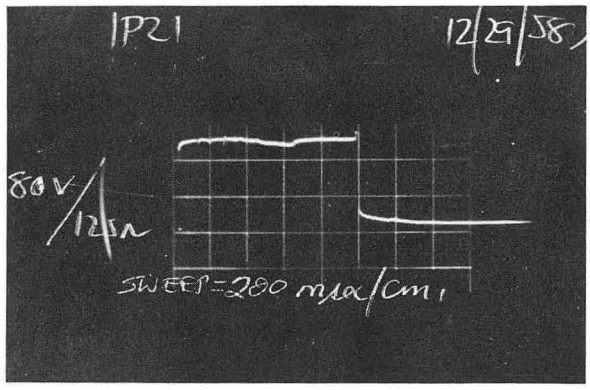

Fig. D41

We would like to consider, in pulsing phototubes, some of the things that have been found out concerning light feedback. We know that the maximum useful voltage on a phototube is often governed by mechanisms of feedback of one type or another. However, if the interdynode voltages are arranged so that the gain is very low, the maximum voltage limit may be considerably higher than otherwise. Then, when the tube is gated on by pulsing the proper dynodes, one obtains a gain that can be higher than that attainable with the normal distribution. It is possible to put onto the dynodes something on the order of 1000 volts peak rf without incurring voltage breakdown. This rf may be made to gate the tube on for a short time when the wave is sweeping the dynodes through the voltage region where the tube can multiply normally. One then obtains one output pulse (or two) per cycle of rf. Or, by gating other dynodes with submultiple frequencies, one obtains pulses at a lower repetition rate. The gating characteristics of several types of phototubes are given in CC8-20.

In using sine waves to do the gating, one can utilize the well-developed rf technology to generate sine waves whose phases and frequencies are accurately controlled. For instance, it is possible to have a pair of oscillators (1 and 2 in Fig. D42) of nearly the same frequency, whose frequency difference and phase difference are adjustable. The output of each oscillator is fed to the dynode of a phototube, the dynodes being displaced from their normal dc potential in the voltage divider. With a dc light source, a series of pulses will come out of each phototube, except that the pulses may be turned on or off, without upsetting the rf, by appropriately gating other

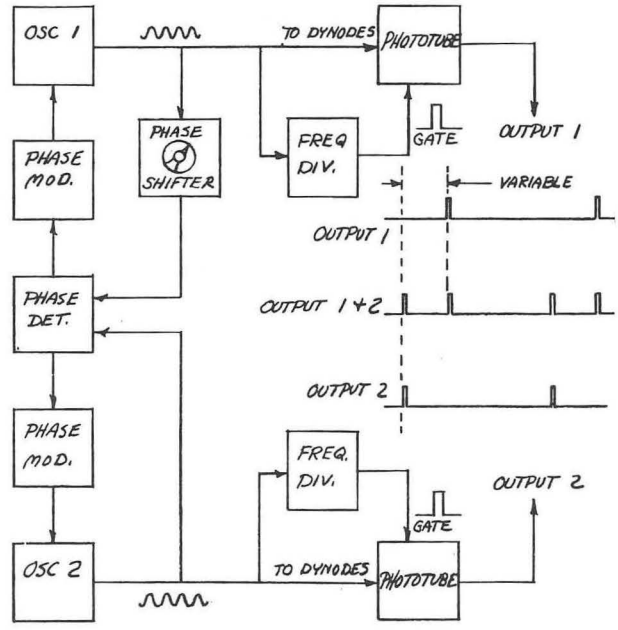

Fig. D42. Double-pulsed generator with quantized variable delay.

dynodes. Thus, as shown in Fig. D42, pulses are produced at a rate which is some submultiple of the oscillator frequency. By initially phasing the oscillators together, one can make the pulses come out of the phototubes at the same time. Then, by turning the phase-shifter knob, one may make the pulses drift apart in a precisely known way. That is, for each turn of the phase shifter, they will have been displaced from each other by one period of the rf. The frequency of the rf may be measured to a high degree of accuracy. Thus, this is a way of generating relatively long time delays with a high degree of accuracy.

D-9. A MILLIMICROSECOND PULSE GENERATOR

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Lawrence Radiation Laboratory
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I should like to describe a millimicrosecond pulse generator designed here at Lawrence Radiation Laboratory. Its output rise time is fast--that is, less than 2.5 mμsec—its maximum repetition rate is 10 Mc, and its maximum output level is 12 volts into 125 ohms.

We feel that such an instrument as this is useful for testing discriminators, coincidence circuits, and scalers. Also it is useful in testing systems for pile-up, base-line shift, and repetition-rate sensitivity. It has a gating feature that can be used to simulate bursts of photomultiplier-tube signals in experiments associated with pulsed accelerators. Figure D43 shows the front panel of the pulse generator.

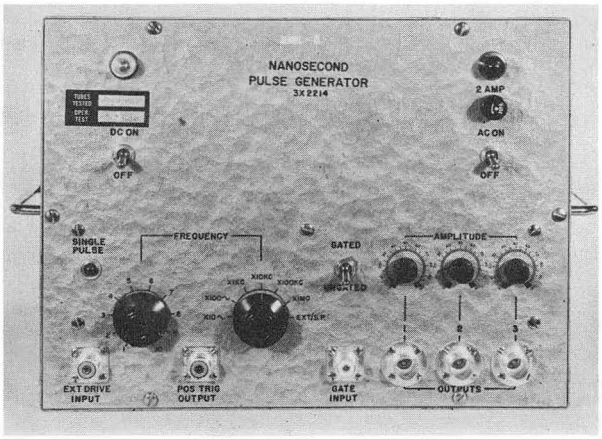


Fig. D43

It has an ac and a dc switch. The two frequency knobs control the repetition rates from 10 cycles to 10 Mc. In the furthest clockwise position of the coarse-frequency control one could put external signals in the "Ext. Drive Input," or single-pulse the unit by a push button. The external drive can be used if one wants stable repetition rates, which this unit does not have. The internal frequency generator is simply a free-running multivibrator.

The gate switch is shown in the ungated position in which all pulses appear at the three output plugs. If this is switched to the gated position, then a +20-volt signal is required at the gate input to get output pulses. The gate input is directly coupled and one is not limited to maximum gate duration. This generator has three separate outputs which are independently controllable for amplitude as well as for pulse width.

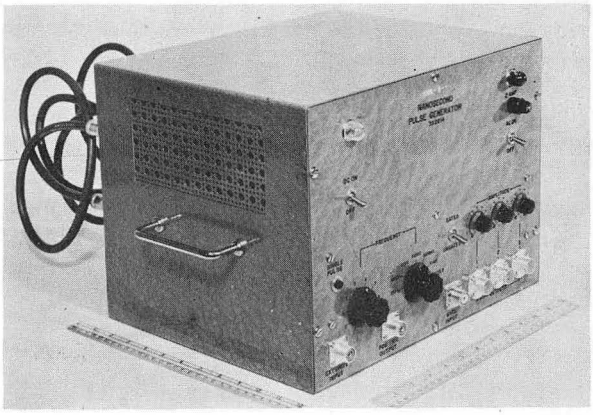
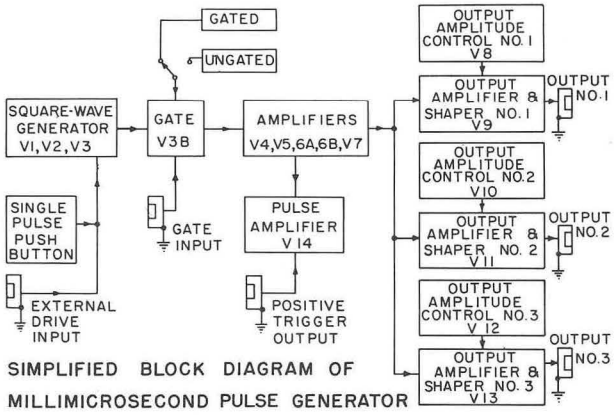


Fig. D44

In Fig. D44 we can see the clipping lines that are plugged in at the rear of the instrument. With these clipping lines the pulse width can be controlled from less than 2.5 mμsec to 25 mμsec. The maximum pulse width is limited by the duty cycle at the highest repetition rate. The duty-cycle limitation of the generator is the plate dissipation of the tubes in the instrument.

The over-all dimensions of the instrument are 14-1/2 in. wide, 11 in. high, and 11-3/4 in. deep, not counting knobs and connectors. The weight is approximately 40 lb. It takes 115-volt ac input. The way the instrument is designed, the input power requirements are a function of the repetition rate. This input power requirement is approximately 200 watts at 10 Mc.

A block diagram of the instrument is shown in Fig. D45. The square-wave generator (a free-running multivibrator) generates the internal



SIMPLIFIED BLOCK DIAGRAM OF MILLIMICROSECOND PULSE GENERATOR

Fig. D45

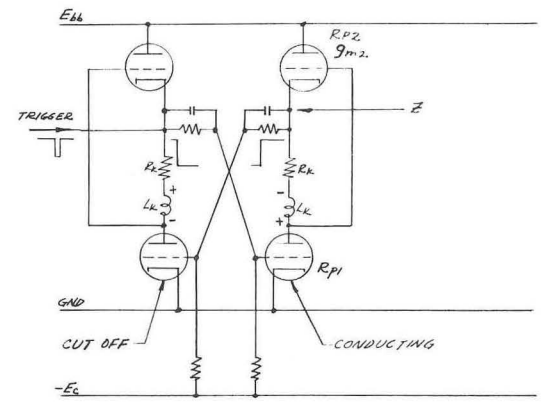


Fig. D46. Basic circuit of fast flip-flop.

frequencies controlled by the two knobs on the front panel. In the seventh position of the coarse-frequency control the square-wave generator becomes a one-shot multivibrator, which is controlled like a Schmitt trigger circuit by the external-drive signal. One can control the output by single-pulsing it or by the external-drive input. The signals are differentiated from the square-wave generator. The square-wave generator is based on the 40-Mc scaler circuit that I described at the first symposium.

The gate signal is not synchronized with the square-wave generator. By switching gate-switch positions one can select gated or ungated operation.

The amplifiers that are lumped together in the next block are actually five amplifiers in cascade, all biased beyond cutoff. Each amplifier in succession is driven into conduction by positive signals. The inversion between amplifiers is done by pulse transformers that are two-to-one stepdown. The reasons for stepdown are twofold: to get the inversion; and to lessen grid input loading to the preceding stage. The amplifiers serve to steepen the rise time of the signals more than to amplify, and the amplitude loss by the two-to-one stepdown transformer is not detrimental.

The signal then goes into three output amplifiers which are 6197 pentodes, each driven by the same line shown in the block diagram. The output is coincident in time, which is useful in coincidence measurements, and one could--if desired--use one of the outputs as a trigger pulse or for initiating timing. The output amplitude is controlled by another tube which is a cathode follower that controls both the plate and screen voltages of the pentode. Because these pentodes are in cutoff and are driven in conduction, one actually drives the tubes into space-charge-limited operation. By controlling the plate and screen voltages, one can limit the output voltage by limiting current output of the pentode.

Figure D46 shows the basic square-wave generator circuit, which is shown as a flip-flop. I like to refer to this configuration as a dynamic plate-load circuit.

Figure D47 demonstrates the steepening of the output rise time of an amplifier if the input pulse is relatively slow-rising. There always is a knee, but if the grid is biased beyond cutoff, the knee that is labeled "a" can be eliminated and "b," which has a relatively faster rise time than the over-all rise of the incoming pulse, can be selected. The output pulse is stepped down by a two-to-one stepdown transformer and inverted to drive the next stage.

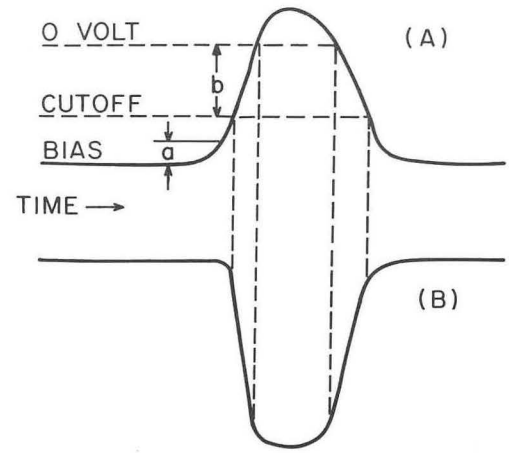


Fig. D47. Wave forms of amplifier input (A) and output (B), indicating steepening of pulse rise time (wave forms not necessarily to same scale).

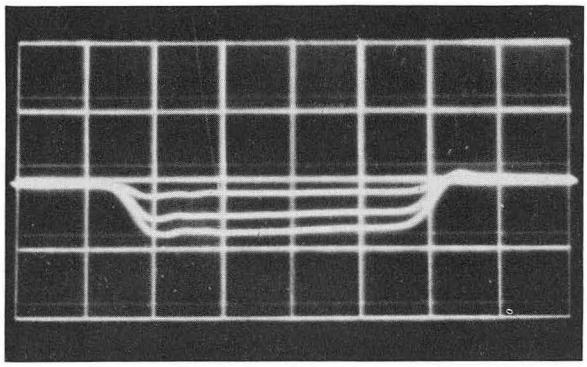


Fig. D48

The output wave form of the pulse generator is shown in Fig. D48. The sweep speed is 5 mμsec/cm, and the vertical sensitivity is 16 v/cm. This is a multiple exposure, indicating the variations of output voltages available. The maximum output pulse obtainable is around 12 v. The pulse width is approximately 20 mμsec. Note the relative flatness of the wave form. One can control the output amplitude by controlling the screen and plate voltages of a pentode when it is driven into space-charge-limited operation, as indicated by this photo.

Figure D49 is another multiple exposure indicating the various pulse widths that can be obtained by use of clipping lines. Here again the sweep speed is 5 mμsec/cm and vertical sensitivity is 16 v/cm.

By use of the gating feature on the instrument, one can get bursts of 10-Mc pulses, as shown in

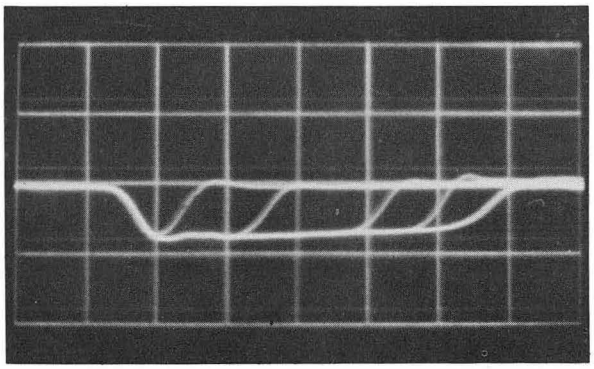


Fig. D49

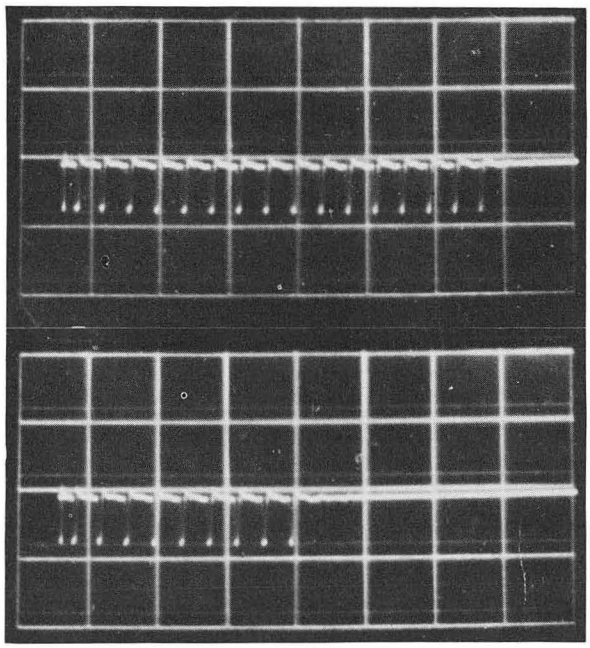


Fig. D50

Fig. D50. The gate is relatively fast; the device can gate in less than 0.1/μsec. The top photo shows 17 pulses. One can also get shorter or longer bursts of pulses. Here the vertical sensitivity is 16 v/cm, and the sweep speed is 0.25 μsec/cm. It might be noted that the burst of pulses as shown here can be used to test discriminators, scalers, and other regenerative circuits. Many times, if one puts a burst of pulses into a discriminator or some regenerative circuit, there may be some additional output pulses after the original input burst has ceased. Or there may be gaps where no output pulse is produced to correspond to the input. This is often true of discriminators in which there is more than one reactive element.

The usefulness of this instrument may be extended by the use of matching transformers to feed into systems having impedance higher or lower than 125 ohms. The output of this instrument is negative only, and there are no provisions for positive output signals. By the use of pulse-inverting transformers, however, the pulses can quite easily be inverted.

E-1. MICROWAVE-GATED PHOTOMULTIPLIERS

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There have already been a number of discussions on how to improve photomultipliers to get higher time resolutions, and I would like to suggest an approach that is not completely new but which to my knowledge has never been seriously tried. This approach is to use a microwave field as a gate on a photomultiplier and, therefore, do the timing measurements with the microwave signal. Since the gating is done with the microwave signal, the stability of the timing is essentially determined by the stability of the microwave frequency (which is, of course, very good), and the accuracy is also determined by the accuracy with which the microwave frequency can be measured. As a result there is a certain amount to be gained by the technique because of the stability and accuracy obtainable. Since the timing is done by the microwave signal, the succeeding electronics need be only as fast as is needed to reduce accidental coincidences to a reasonable level. If a phototube is gated by microwaves a certain phase angle is picked out in which the tube is on. The rest of the time the electrons are returned to the photocathode by the microwave electric field and no pulse is transmitted to succeeding equipment. A second tube some distance away in the beam, connected in coincidence with the first one, and also gated by microwaves, will have to have the microwave gate open at the time that the particles arrive at it in order to record a pulse. If it does not have the gate open at this time the particles will not be counted by that tube and, of course, no coincidence will be recorded. The microwave signal, therefore, does the timing and, if a high enough microwave frequency were used it should be possible to get very good timing accuracy. Of course, some difficulties come to mind immediately. With a couple of tubes gated in this manner the first tube picks out only a certain fraction of the beam. If absolute rejection of the particles is desired the tubes must be gated off at least 50% of the time and preferably slightly more, and if that is done less than 50% of the beam is used. But, provided the microwave system is reasonably simple, it is clear that it is possible to put another set of similar counters in between, properly phased relative to the first set, and by means of two such sets of counters almost the entire beam can be used. With a linac operating at high frequency, such as the Stanford machine, only one counter is needed, since it can be phased with the rf system in the machine, so that for a machine of that type the problem becomes much simpler.

The question is how to gate a photomultiplier, and there are a variety of ways of going about this. As a matter of fact, there are about as many ways of gating as there are methods of generating the microwaves in the first place. Out of this variety of methods we must pick one that looks as though it might be reasonably good and also reasonably simple to build and operate. One of the problems is that for the electrons coming from different parts of the photocathode there are certain transit-time spreads in getting to the place where the microwave gate is applied. Also the electrons have a certain initial velocity distribution, and because of this an additional spread in the transit time is introduced. If better resolutions than are practical with present-day counters are desired these transit-time spreads should be less than 10^{-10} sec. It is easy to see that not very far from the photocathode the timing will be completely washed out by the transit-time effect for reasonable potentials. My own approach to the problem has been to try to do the gating right on the photocathode of the photomultiplier--that is, to apply the microwave electric fields directly to the photocathode of the photomultiplier.

If a microwave electric field and also a dc field are applied to the photocathode, they are represented by the top equation,

$$E = E_0 \sin(\omega t + \delta) + E_1$$

(shown in Fig. E1). Then, by simply integrating the equation for Z, one obtains the distance away from the photocathode. This is quite a messy equation, and in order to get a feeling for what it says, first forget about the term in E_1. In a plot of the rest of the equation the solid curve separates the cutoff region from a region in which electrons would continue to get away from the photocathode to the dynode structure

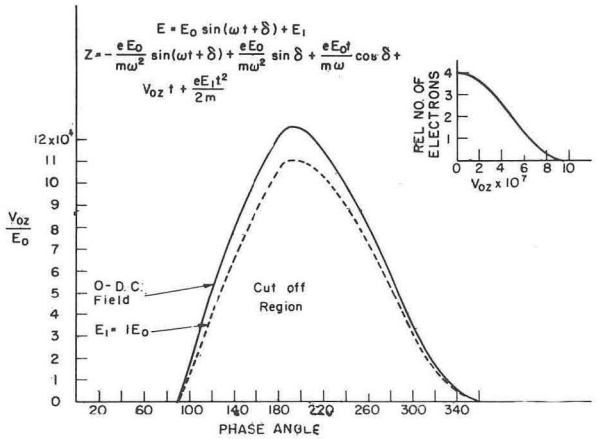

Fig. E1

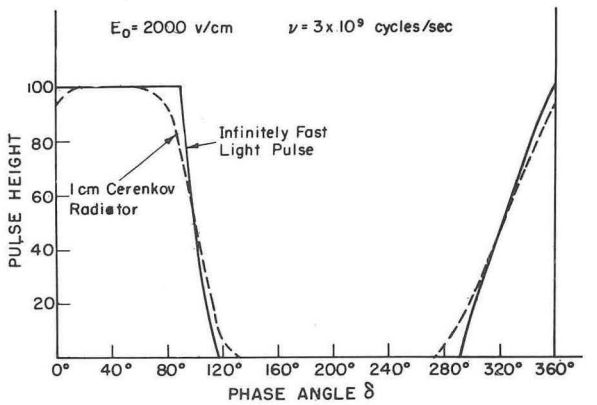

Fig. E2

of the phototube. This is plotted for 3000 Mc.

The effect of the dc field for $E_1 = 0.1\ E_0$ is shown by the dotted line. In general it will turn out that E_1 may be neglected as far as gating is concerned, because E_0 has to be much larger than E_1 in all cases, so that the effect is not very important. It is possible then—at least in principle—to cut off the tube with microwaves three-quarters of the time; this satisfies the requirement that for absolute rejection of the particles, the tube must be cut off more than one-half the time.

The amount of phase-angle cutoff is a function of the initial velocity of the electrons as well as of E_0, and the initial velocity of the electrons has a certain distribution, therefore this initial velocity will mess up that fraction of the cycle during which the microwave gate is on. Some crude guesses of a velocity distribution give the curve in the upper right. The curve was obtained by considering Čerenkov light from a quartz radiator, a cesium-antimony cathode, and a cosine-function distribution of direction for the photoelectrons. Folding the velocity distribution into the V_{0z}/E_0 curve for a microwave field at 2000 volts/cm and a frequency of 3×10^9 (which would correspond to a time resolution somewhere around 10^{-10} sec) gives the curve of Fig. E2. The solid curve is for an infinitely fast light pulse into the phototube. The phase angle for cutoff can be made sharper by use of a larger microwave field. If that is done, the duty cycle is reduced somewhat. A field of 2000 v/cm is quite a reasonable one. It doesn't take too much microwave power or a high-Q cavity to get fields of this order of magnitude. To illustrate another problem at these time resolutions, I have also drawn a dotted curve which shows the effect of a 1-cm-thick Čerenkov radiator. As can be seen, this is probably as thick a radiator as you can use. If a Čerenkov radiator is much thicker than 1 cm the time resolution is washed out.

I might say a few words about this. In the search for configurations in which to put a Čerenkov radiator in front of a photocathode, there are two general approaches. One is to use a tubular type of Čerenkov radiator and then an optical focusing system to focus the light on the photocathode. In this case the diameter of the Čerenkov radiator cannot be much greater than 1 cm, or particles coming in on one side or the other will have their timing washed out. The other way is to put a thin slab of Čerenkov radiator right on the surface of the photocathode, but then again you are limited to about 1 cm thickness. In order to get the maximum Čerenkov light it would be nice to go down into the ultraviolet, and for that reason I have picked quartz for a radiator. By gating on the photocathode, it is possible to calculate and set up in advance an arrangement of equipment to reject or accept particles of a given velocity without ambiguity due to unknown time delays. In other words, it is unnecessary to calibrate the equipment for rejection or acceptance of particular kinds of particles. This may have certain advantages and it may save time in many cases.

I have tried to gate commercial photomultipliers by using microwaves. There are several problems involved. One is that the geometry of the commercial phototubes does not lend itself very readily to being gated. The tubes are of such a geometry that in order to gate them you have to cut a rather large hole in the side of the microwave cavity. This lowers the Q of the cavity. It means that a large amount of power must be used to get large fields. So far, I have used about 50 watts of power in a cavity. The Q of the cavity was quite low, and a maximum of 300 to

350 v was attained on the photocathode. It is a little difficult to tell in these geometries just how much of a field you have on the photocathode, because when a hole is cut in the side of the cavity it disturbs the field configuration badly. The result is that at 300 v the curve of Fig. E2, instead of coming all the way down to zero, comes down to about 60% of its maximum value. It does not give complete gating. However, with a Čerenkov radiator in front of this, and using cosmic rays, I have been able to show definitely (within the statistics, of course, because you have only a relatively small number of photoelectrons to work with) that the pulse height does indeed drop corresponding to this curve. This was gating one phototube. The next problem, and this is really the crucial test, is to take two tubes of the same type, gate them with a microwave signal having a known phase between them, and then, by shifting this phase, see whether you actually do get coincidences or not. So far I have not been at an accelerator to do this and the cosmic-ray intensity is relatively low. There are very few photoelectrons and therefore statistics on the sizes of the pulses also confuse the results, so that when the gating is done with pulses going down to 60% of the maximum value it is very difficult to see any effect. I would say only that the experiments are not in disagreement with the predicted curves.

Because of the problem of coupling, I have looked into the possibility of designing a special tube that might work better. The tube design is shown in Fig. E3. There probably are other designs that could be used, but this one seems relatively simple to build. A standard photomultiplier dynode structure can be used, which should be as fast as possible in order to keep down accidental coincidences. The photocathode is in a microwave cavity with the microwave input at the top. A quartz Čerenkov radiator about 1 cm thick is used, the geometry allowing quite good collection of the light. The photosurface is deposited right on the quartz radiator and the vacuum seal would be made at the radiator, although it could be made at the microwave input using a mica window. The field configuration in this particular cavity has the shape shown by the dotted lines. The Z component of the electric field should be a maximum at the surface of the Čerenkov radiator in order to gate the tube with maximum effectiveness. At these frequencies the photoelectrons go only about 0.01 mm before they turn around and go back into the photocathode. There are a large number of microwave cycles as the electrons go from the photocathode to the first dynode. The microwaves have practically no effect on the transit time, however. The other worry is that radial field component in the cavity might cause a defocusing effect. This is not true, however, since the microwave frequency is so high that a very large number of cycles occur as the electron travels between the quartz Čerenkov radiator and the photomultiplier structure. The radial field component is zero at the quartz Čerenkov radiator. The rate at which the radial field increases as seen by the electron is much lower than the microwave frequency, and as a result the electron just jitters back and forth a small amount, with a gradually increasing amplitude until it gets to the center of the tube, and a decreasing amplitude until it gets down to the photomultiplier structure. The effect is so small that it can be completely neglected. The one thing that does occur is a velocity modulation of the electrons arriving at the first dynode. This velocity modulation with a 2000-v field is of the order of 20%, so that there is about a 10% energy spread of the electrons. However, the dynode secondary-emission characteristic is flat enough so that this is unimportant.

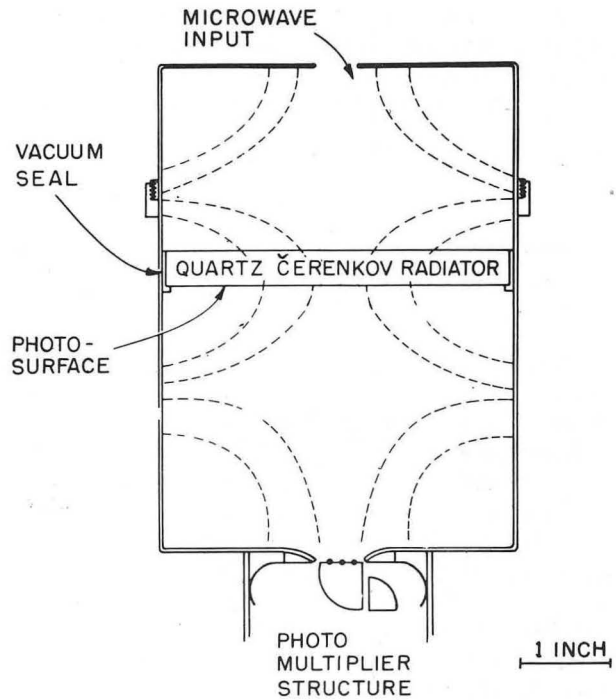

Fig. E3. Microwave phototube.

At 3000 Mc, the time resolution attainable is of the order of 10^{-10} sec. At higher frequencies several factors become important which set an upper limit on the resolution. One is the need for a tube of reasonable size. At 3×10^{9} cycles a tube on the order of 4 in. in diameter can be

made. For 3-cm waves the size of the tube would go down correspondingly. Another limiting factor is the thickness of the Čerenkov radiator, since a thinner radiator would not produce sufficient light.

Discussion

Horwitz: Would you use three tubes to avoid getting counts with particles resolved by a full wave length, or is there a simpler way?

Meyer: This would be the method you would have to use. You would have to use another tube to be sure that you were getting rid of particles that skipped a whole cycle. In some experiments this probably wouldn't be necessary because you might have a mixed beam, but a beam that was still pure enough that you were fairly sure that unwanted particles weren't getting through. But if you really wanted to be sure you might want to line up more than two tubes. In fact, what you might want to do is use a number of tubes, which would then get you down to the range where the photomultiplier structure could pick up the rest of the timing.

Piccioni: I guess you told in your last words what I wanted to say, that is, you could still make electronic coincidence with the photomultiplier output and decide.

Horwitz: Yes, except you're down one cycle wave, which is very close to 10^{-10}, and you can't as yet do electronic coincidence of 10^{-10} sec.

Meyer: It isn't as bad as you think because of course one cycle is 3×10^{-10}, so that three tubes would take you up almost to 10^{-9}, and then you might be in pretty good shape to use an ordinary tube.

Caldwell: I wonder about that geometry shown in Fig. E3. It looks as if the beam would have to go into the dynode structure.

Meyer: The particular way in which I have it drawn, it would have to go into the dynode structure. You can put the dynodes out to one side, for example, if you wish. In fact, this is what has been proposed.

Miller: I believe that with this field, the cavity would give you about 7 gauss magnetic field. What would the electron orbits in that magnetic field in a time-loss study look like?

Meyer: I have calculated this, and it seems to be somewhat less than the electric effect. The effect is almost zero during the first cycle, but you might wonder how it would go as it were integrated through the cavity.

Roberts: What can be done with existing tubes with use of existing electrodes?

Meyer: You mean, to do the gating with present electrodes? I don't think the configurations of present commercial tubes are very favorable for this. There are no phototubes I know of with a grid in a proper location to do this within the allowable transit time (i.e., to keep down the transit-time spread).

Roberts: There must be some minimum or maximum frequency. I mean, you can certainly gate a tube with a millisecond.

Meyer: Certainly.

Roberts: What's the limit?

Myers: My guess would be several times 10^{-9} sec, which wouldn't help you any. I mean, this you could do with ordinary coincidence circuits.

E-2. PULSE-HEIGHT ANAYSIS AND TIMING MEASUREMENTS OF FAST PULSES*

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The circuits and equipment described here were developed in connection with experiments using the electron beam from the Stanford high-energy electron accelerator. The properties of this accelerator are quite different from those of most circular machines. It is a pulsed accelerator with a very low duty cycle and short intense beam. The pulse-repetition rate is 60 per sec. The pulse width is on the order of 100 mμsec, but can be extended under some circumstances to as much as 500 mμsec and is frequently operated with a width of 50 mμsec. During the accelerator pulse the electron current into the experimental area may approach 1/4 amp at energies up to 700 Mev. In many experiments scintillation or Čerenkov detectors must be shielded with great care to avoid pile-up of events, for the instantaneous counting rates are frequently in the range between 10^7 and 10^8 counts/second.

Most of these pulses arise from photo- and electroproduced neutrons which have a long mean free path in the counter shielding. These give rise to counts either from the detection of knock-on protons in hydrogenous scintillators, or of neutron-capture γ rays in Čerenkov counters or NaI(Tl) detectors.

Unshielded counters are overloaded during the machine pulse in almost all electron experiments. Small counters with a sensitive volume of less than 20 in.^{3} require from 15 to 60 tons of iron or iron-loaded concrete to reduce this overload to a manageable level. A clearing magnet is usually necessary, therefore the detector cannot view any target material directly in the primary beam. In the electron-scattering program magnets are used to momentum-analyze scattered electrons or nuclear disintegration fragments including protons, deuterons, etc. In all these experiments it is necessary to pulse-height-analyze the counter spectrum either to determine an integral discrimination level or to use the detector as an energy analyzer.

* Supported by the joint program of the Office of Naval Research, the Atomic Energy Commission, and the Air Force Office of Scientific Research.

The output of a shielded Čerenkov counter during a machine pulse exhibits a large number of very small pulses from background with an occasional large pulse from a momentum-analyzed particle. The pulse-height distribution of the background counts has a well-defined peak at low pulse height and goes to zero below this. This characteristic spectrum is a consequence of the high instantaneous counting rate. Pulses overlap and pile up so that it becomes unlikely that a single small pulse will be observed. Above this pile-up peak lies the distribution of pulses from desired events. The mean pulse height of pile-up pulses is a very sensitive function of the pulse width from the photomultiplier. In the cases considered here the pulse widths were about 7 mμsec—characteristic of an RCA 6810A driving a 100-ohm transmission.

The pulse-height distribution of real events from a Čerenkov counter has a single peak with a steep slope on the low-pulse-height side and a broad tail on the other from electromagnetic shower production in the body of the radiator.

It is necessary to use very fast electronics to select these desired pulses for pulse-height analysis with conventional slow analyzers. In Fig. E4 we show a fast linear gate which can be used to select these pulses, triggered either by another counter used in a telescope configuration or by a fast integral discriminator operated from the pulse spectrum.

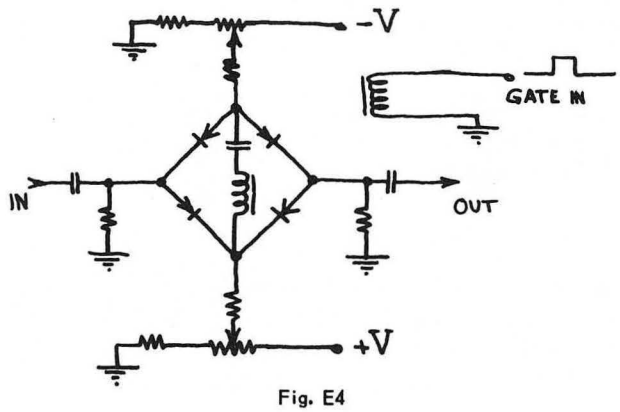

Fig. E4

The gate is a simple symmetrical configuration of four back-biased diodes. The speed depends on the choice of diodes, the transformer, and the properties of the gating pulse. It can be constructed so as to open and close in about 10 mμsec. With longer time constants and a transformer with larger core inductance it can be kept open for many microseconds. The symmetrical properties of the gate in principle eliminate a pedestal at the output. Small switching transients of rms value zero do appear, which will not affect subsequent slow electronics. Small readjustments of the back-bias voltages can compensate for diode nonuniformity, and the output can be adjusted to contain no pedestal. The gate accepts pulses of either sign.

With information arriving at a very high rate, but for short periods, it would be convenient if it were possible to store a pulse train from a counter. During the period between beam pulses this information would be time and pulse-height analyzed. We have designed, but not constructed, an instrument to do this with a time resolution which could be made very high. It is essentially an n-point sampling device. The pulse train to be investigated is sent into a delay line separated into n segments. At the end of each segment is a gate, normally closed, whose output goes to a similar n-segment delay line with a much slower velocity of propagation. Before the first of the pulse train has reached the termination of the fast delay line a gating pulse opens the n gates simultaneously and transfers an n-point sample of the pulse train to the slow delay line. The output of the slow delay line can then be analyzed by conventional techniques. The factor by which the time scale would be stretched could be quite large. A configuration that suggests itself is an analog of a distributed amplifier. The grid line of an array of gate tubes would be a lumped-constant line of a propagation velocity similar to those of fast amplifiers. The plate line has a slow propagation velocity. The second control grids, if gated simultaneously, would result in a time resolution twice that achieved by a gating pulse applied to the grids by a delay line similar to the first grid line but gated in opposite sequence. This laboratory has not been able to do more than consider the design of this device, although the need for it continues to exist.

In selecting those Čerenkov counter pulses that arise from desired events we are aided by the fact that many of the spurious events give lower pulse amplitudes than real events. A fast integral discriminator of the Moody type can be used to select the larger pulses, provided an accurate method is available for locating the discrimination level. The pulse-height distribution arising from electrons traversing a Čerenkov counter has a characteristic structure that in principle allows an accurate integral level to be selected that will reject only a small fraction of the real events yet include only a small background contribution. To record a satisfactory pulse-height distribution one needs a slow multichannel pulse-height analyzer; we use a 256-channel analyzer. To define the firing level of the integral discriminator we take two pulse-height spectra, one in coincidence with the discriminator output. The integral-discriminator firing level may then be found from the cutoff point of the second pulse-height spectrum.

We have developed a circuit which prepares the very fast pulses from the Čerenkov counter so that they can be analyzed by equipment requiring an input width of about 2 μsec. Its purpose is to eliminate the effect of the large number of small pulses that surround the pulse to be analyzed. That is, it must stretch a large pulse of about 7 mμsec duration with a decay constant of about 1 μsec, yet include no contribution from small pulses preceding or succeeding the desired event by more than 10 to 15 mμsec. A circuit that accomplishes this is shown in Fig. E5. The fast stretch is accomplished by the charging of a small capacitance by a cathode follower, with a large cathode resistor to slow the decay. A second stage incorporating a semiconductor diode (Transition T6) completes the stretch. The circuit will generate an output proportional to the amplitude of the largest pulse in a pulse train, provided the remaining pulses are not too large.

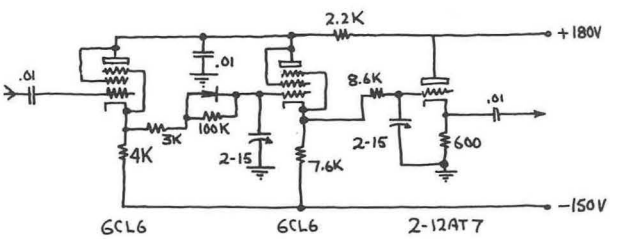

Fig. E5

We have used this to allow pulse-height analysis of the output of a NaI(Tl) counter placed at the focus of the Stanford 36-in. magnetic spectrometer detecting heavy fragments from electron disintegration of nuclei. The pulse-height distributions can be analyzed easily to yield excellent separation of protons, deuterons, pions, etc. With NaI(Tl) counters a low photo-

multiplier anode resistor is necessary to develop a pulse similar in shape to the light pulse, with subsequent delay-line pulse shaping to a width of about 10 mμsec. This pulse is stretched in the circuit described above and then pulse-height analyzed.

The linearity of response of the stretcher is shown in Fig. E6. The discontinuity near the origin is a consequence of the low current in the first cathode follower. Above this is a region of satisfactory linearity.

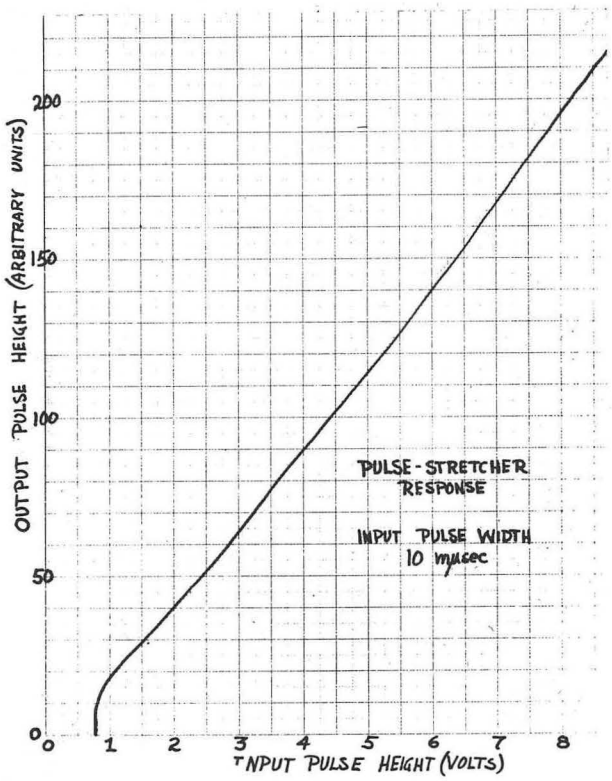

Fig. E6

There are a number of discussions at the meeting concerning large counter arrays. We have in operation a ten-channel prototype of a multi-element counter array which when complete will scan the useful focal plane of the Stanford 36-in. magnetic spectrometer. We have nearly completed twenty more channels, each with a momentum acceptance of 0.1%. The goal will be 50 channels in each of two magnetic analyzers. This counter array has been described.[1] Each scintillation counter in the array is coupled to a 3/4-in. 10-stage photomultiplier, and groups of 10 counters are backed by a Čerenkov counter. Fast coincidences are required: we found that a coincidence resolving time of about 20 mμsec was the minimum practical with the large array.

[1] IRE Transactions *NS-5*, 190 (Dec. 1958).

Attempts to decrease the size of small scintillation counters, which must be operated adjacent to one another, are limited by the size of the smallest photomultipliers available. We could use end-window photomultipliers smaller than the 3/4-in.-diameter ones presently available.

We are constructing complete automatic control of most of the important parameters of a typical electron-scattering experiment using the 36-in. magnetic spectrometer, and a computer-type memory to store information from the counters. A number of separate sets of experimental parameters are stored in a central memory. Data are taken sequentially at different preselected magnetic fields, targets, etc. Separate circuits require that parameters do not vary from their preselected values during data taking.

A problem consequent on the use of the first model of the counter array is that we collect data at a rate exceeding our capacity to analyze it. We are faced with the problem of evaluating all the data on a computer. The programming of this evaluation has been started, using Stanford's IBM 650 computer. We expect as a last step to punch the data from the experimental equipment on tape so that no manual transcription of information will be necessary.

Discussion

Garwin: A question about this gate circuit which in principle has no pedestal—What's the speed of the circuit, the dynamic range? What kind of diodes do you use? Do you have to match them? And what's the real pedestal?

Kendall: The pedestal you can tune out by varying the bias. The back biases are individually arranged and what pedestal comes through is a consequence of cutting more current off in the lower grid part of the bridge than the upper bridge. You can tune the pedestal out so that it has rms value zero, and you get the switching transients at each end by altering the knobs. The dynamic range is set simply by the diodes used and the available back bias that you can put on, the only criterion being that the gating pulse must remove the back bias. We've used this in slow circuits (0.3μsec) with conventional diodes and conventional blocking oscillators, and one can get a dynamic range of 15:1, I believe. I haven't measured this in detail. This is a point we tend not to go into, you see, tending to alter a gain somewhere rather than rely on a large dynamic range. The diodes are T6's and the speed of the thing has never been probed in

detail; it is largely a question of how well you can supply a gating pulse. It depends more on the input parameters than on the actual electrical construction of the circuit. It works satisfactorily for 10- to 15-μsec gate pulse widths. You didn't ask this question, but the pulse transformer is more the key to this than anything else. We have wound small ones on ferrite toroids which seem to work exceedingly well for the short times.

Gatti: I would like to know how many stopping points you have in your device, and how you match the transconductances of the tubes.

Kendall: We have not constructed that, I'm sorry to say. We haven't got the manpower to do it, so it exists only as a design.

Gatti: I can say that I think the difficulties will be to match two parameters for each tube, that is, the transconductances and absolute current when the current has been switched on by the gating pulse.

Kendall: I think that's very likely correct, and it would be in the same category as the trimming on the Tektronix delay-line scopes. One would simply have to match it point by point by putting in a uniform pulse, for example, rather than having a pulse train in the delay line. You could simply raise the line to a nonzero dc level, put in a gate pulse, and then adjust each one until the output was uniform. It could be empirically adjusted.

Gatti: It seems to me that there is another parameter. This is for gating the equal jumping-off points. You have to get the transconductances equal.

Kendall: You have to have the transconductances equal; this is correct. And whether one is able to do this—to make a device which is exceedingly uniform in the sense of 1% equality--or whether you just get something out (which would be principally what would interest me) I think is an open question. You could certainly do it to first approximation.

Roberts: I would like to say a few words about these large photoscope arrays of fibers, if I could take a minute. I always get unhappy when I see people starting to use large numbers of very small fibers, each one with its own separate photomultiplier; I would like to point out that a scheme has been suggested by Dr. Ernest Hare at Rochester (which I haven't been able to get him to publish yet), which is a method for using very large numbers of fibers without having to have a photomultiplier and an associated amplifier for every fiber, but to make the number of photomultipliers proportional simply to the logarithm of the number of fibers. This allows you to go up into a considerably bigger range of number of fibers--it begins to get pretty expensive after you get around a hundred or so. This is a simple coding scheme, which I will illustrate by using a decimal coding system, although it is equally applicable with a binary or any other code. We take these fibers that are arranged in the focal plane of the spectrometer (and notice that each one has two ends), and take the light out with a light pipe from each end. Let's suppose now that we arrange 100 fibers in 10 groups of 10 each and number them from 0 to 99. Connect one end of every tenth fiber--that is, Numbers 0, 10, 20, 30--so that they all terminate in one large 2-in. multiplier tube. The next tube would have numbers 1, 11, 21, and 31. That makes ten tubes. Then we take the other ends of Numbers 0 through 9 and put them on one tube, 10 through 19 and put them on a second tube, and so on. Now take coincidences between any one tube on the "tens" side and any one tube on the "units" side, and the coincidences will tell us which of the fibers have gone off, because each fiber will give light in both directions. This, then, is a decimal coding system in which the number of multipliers is now proportional to the logarithm, since it is a digital system. There is one disadvantage to this system which is immediately obvious, and that is that there is an ambiguity in case two particles come in at once, that is if Fibers No. 17 and No. 63 go off, it could equally well be interpreted as Nos. 13 and 67. There are ways of getting around this, though, by having two arrays of fibers, in which case you can run the capacity of the system up. But if you really are thinking of getting into large numbers of fibers, this method will work. It does require a number of coincidence circuits—of course you have to have a matrix of coincidences between all pairs of these twenty tubes. But you have to have this output in any case if you are going to have a hundred channels. If you want to get a hundred output possibilities you must have a hundred output circuits. At least it avoids all the circuitry for the multipliers and the expense of the multiplier circuits.

Birge: I wondered if the people who were making the photomultiplier tubes had thought about going to the opposite extreme, namely of using finite-sized filaments on finite-resolution tubes. In other words, there is nothing magic as I see it

about 0.1-mm or 1-mm fibers. If you go to 1/4 inch, say, and go into a tube that has a finite number of openings--such as a 1/4-in. opening as in the channel multipliers of the Midway type--it seems to me that there might be an easy solution to these problems in that direction.

Kendall: Let me indicate one other device that might be useful in this respect. This was devised by Martin Deutsch at MIT, and is in effect even simpler than this. If you have a scintillator, and view each end of it with photomultipliers, then the ratio of the light that is collected by one photomultiplier to the light collected by the other will tell you where the particle went through, and by a simple process of division you can generate a pulse whose amplitude depends on the position of the initial event. Such a device has been built and tested, and gives quite a high spatial resolution. This was considered for our device at Stanford, but for minor reasons it is not practical; principally the enormous pile-up of pulses makes it difficult to use a large scintillator. But around an accelerator where one could tolerate a large scintillator looked at by two phototubes this works quite well.

E-3. SEMICONDUCTER DEVICES IN COINCIDENCE CIRCUITS

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My story begins about one year ago when commercially available transistors began to reach interesting frequencies. We immediately began to look into the possibilities of using them for counting applications. Among the apparatus we brought out here to Berkeley this past summer to do an experiment at the Bevatron was a simple three-counter monitor telescope which was completely transistorized. With this experience I became very enthusiastic about the potentialities of transistors in high-energy physics. And now I have been asked to justify my enthusiasm in public.

A number of us at Princeton have transistorized most of the electronics that we customarily use in doing experiments, and I will discuss two of these circuits as an illustration of what can be done. I would, initially, like to emphasize two of the advantages of the transistor which are important in the applications that concern us. First, the transistor has a ratio of transconductance to current of about 40 (at room temperature). This is to be compared with the value for good vacuum tubes (e.g., E 180F), which is around 2. This means that the signal level (for the same percentage change in current) can be reduced by a factor of about 20 when transistors are involved. As we will see, this factor of 20 makes it possible to drive coincidence circuits directly from 11-stage phototubes.

The second pertinent advantage is the frequency response of the transistor. Transistors are now being produced with α-cutoff frequencies of 3000 Mc. There are indications that these techniques might be refined to give a cutoff frequency of perhaps 20,000 Mc. The α-cutoff frequency corresponds roughly (within, perhaps, a factor of 2) to the gain-bandwidth product of a vacuum tube. This gain-bandwidth product for the vacuum tubes we have become accustomed to using is around 200 to 250 Mc.

However, in the circuits that I will discuss we have restricted ourselves to more modest transistors, in particular, to those in the 200-Mc range. We achieve a performance that is slightly superior to what can be done with vacuum tubes. There are disadvantages. At the low signal level, the stray-signal pickup problem is undoubtedly more severe. We have not had enough experience to say anything about this particular problem. Furthermore (and this is a very obvious statement), power output and good frequency response are completely incompatible qualities. Fortunately, in counter techniques one seldom requires more power than is necessary to, say, activate a galvanometer.

Figure E7 shows one of our basic building blocks, a discrimination circuit which is a development by Dr. Pierre Piroué. It is essentially an ac-coupled Schmidt circuit with an emitter-follower on the output. Perhaps of most interest to this audience is that this simple device can give an output pulse 35 mμsec in duration. Furthermore, its recovery is essentially complete in 60 mμsec. The discriminator accepts an input voltage range of 0.04 to 1.7 volts. The device works much better than the Philips tube (EFP-60) regenerative circuits that most of us have become accustomed to using. We use the discriminator at the input to scaling circuits. We have a standard scale of 64 with a 0.1-μsec resolving time which we use as a prescale. The whole scaler uses 125 mw, though special techniques are necessary to get good performance with this resolution.

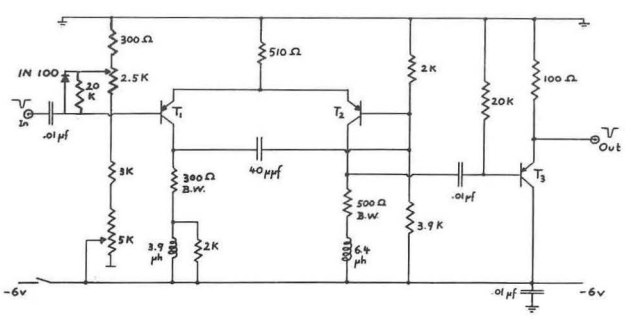

Fig. E7

We also use the discriminator on the output of coincidence circuits. The particular circuit we use is shown in Fig. E8. This circuit diagram shows a double coincidence. There appears to be no difficulty in using many channels. Positive

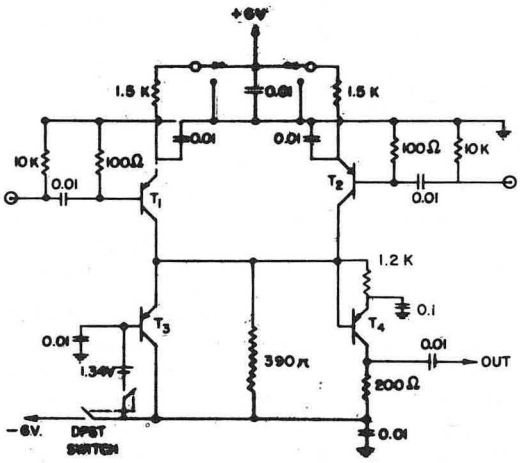

Fig. E8

pulses are applied to the bases of T_1 and T_2. The collector signals are added nonlinearly across the emitter impedance of T_3; T_3 carries a quiescent current equal to the collective current of T_1 or T_2. Thus there is no substantial swing in the emitter voltage of T_3 if either T_1 or T_2 is turned off individually. If, however, coincidence pulses arrive, the current through the 390-ohm resistor is applied to the base of T_4, this transistor is saturated, and it bottoms--hard. A positive output is taken across the 200-ohm resistor in the collector of T_4. The output is conveniently stretched by making T_4 a transistor with a long hole-storage time. The circuit as shown will deliver full output with an input signal of ~ 70 to 100 mv. We have improved the resolution that can be obtained with 6342 phototube pulses by using a shorted transmission line on the collectors of T_1 and T_2. With a 3-ft 300-ohm shortened line, the resolution (cable) curve shown in Fig. E9 is obtained. The distinctive feature is the rise from zero to the plateau in about 2 ft of cable. This curve was obtained with a pair of counters, using cosmic-ray μ mesons. The size of the counters was such that the dispersion in the arrival time of the light at the phototubes was about 1/2 mμsec. All the transistors in these two circuits are 2N501's.

The principal thing I would like to emphasize is that without too much effort one can really do very well with transistors. They are just now becoming very fashionable in counter techniques--and with great justification.

Discussion

Mack: What is the purpose of transistors T_3 and T_4 in your coincidence circuit?

Fitch: T_3 is for the nonlinear addition of the pulses. We like to hold the base of T_3 firmly, so we

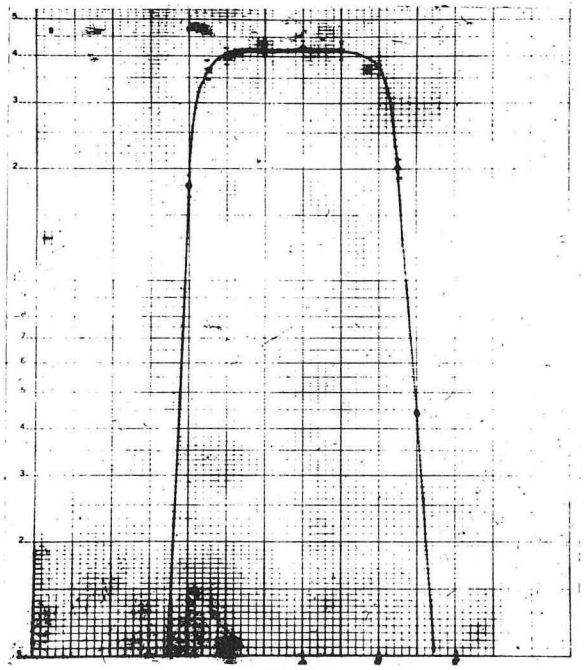

Fig. E9

can use the mercury battery for the bias supply.

Wenzel: I would like to ask about the 35-mμsec discriminator pulse. How big was it?

Fitch: Two volts.

Rogers: What does the discriminator do if it is hit with a wide pulse or a large overload; is the output multiple?

Fitch: Absolutely—it is ac-coupled. It will produce multiple outputs if the input is too long. In our application we don't have to worry about this. We find that we lose speed if we try to dc-couple the device.

Sands: Have you mentioned the sensitivity—the firing level as a function of pulse width?

Fitch: Yes, the discrimination level remains essentially constant for pulses as short as 30 mμsec. Pulses of shorter duration must be larger to trigger the regenerative action. I don't have with me any quantitive information on this point.

Garwin: When you projected the delay curve you mentioned that the resolution could be increased merely by reducing the length of the clipping line. For the 2N501 transistor, at what point do the transistors limit?

Fitch: I don't know. We haven't tried anything shorter than 3 ft as yet.

Cork: How many decades did you follow the delay curve?

Fitch: About three decades.

E-4. SIMPLIFIED COINCIDENCE CIRCUITS USING TRANSISTORS AND DIODES

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Abstract

The fast semiconductor diodes and transistors now available make it possible to design counting circuits that are as fast as standard fast vacuum tube circuits. A simple coincidence circuit using these devices is described. The measured threshold and resolving-time characteristics are given. The circuit is free from the difficulty present in some vacuum tube circuits wherein a coincidence count can be made with a pulse below the threshold at one input if a pulse considerably above the threshold is present at another input. The changes in counting arrangements which the simplicity of these circuits permits are discussed.

With the appearance of fast diodes and transistors, which can be switched on or off in a few millimicroseconds, it becomes possible to build coincidence circuits which have resolution time and threshold properties similar to the conventional Garwin circuit,[1] but which are much simpler to construct. This presentation describes tests made on some circuits of this type.

Coincidence Circuit for Negative Pulses

Figure E10 shows a diode double-coincidence circuit for negative input pulses, with a transistor limiting amplifier output. The diode coincidence circuit is just a standard "and" circuit familiar from computer applications. The 180-ohm resistors match the input coaxial cables and assure equal division of the diode currents almost independently of the diode characteristics. The diode current is not critical, but was chosen to be 5 ma in each diode for this circuit. The current is set by the 2.2-K resistor to the -22.5-v battery. Because of the forward drop of about 0.4 v in the S570G diodes[2] the common junction of the diodes is normally at about -1.3 v from ground. The base of the grounded-emitter transistor limiting amplifier is directly connected to the common junction of the diodes, so that when a pulse is present at both the inputs, currents up to 10 ma can be switched to the transistor base. The rate of current switching is determined by stored-charge effects in the diodes and wiring capacities in the base circuit. The transistor emitter is connected to a bypassed -2v bias to keep the transistor cut off. The collector may be caught by a diode at some convenient dc level such as -8 v to allow a 6-v positive swing to saturation, and to speed the return after the output pulse. With a 2N501 transistor,[3] output pulses

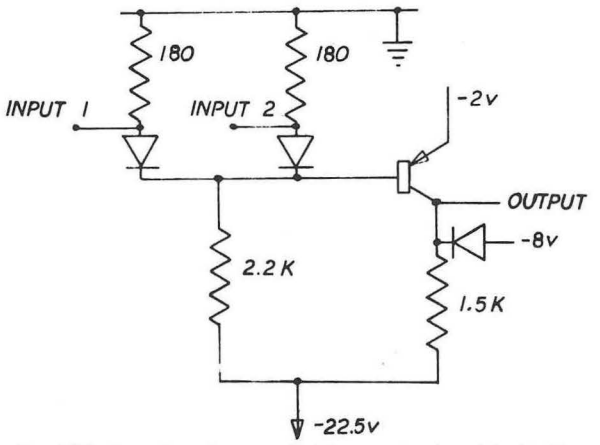

Fig. E10. Negative input coincidence circuit with limiting amplifier output. In this and later figures, all diodes are type S570G and transistors are type 2N501.

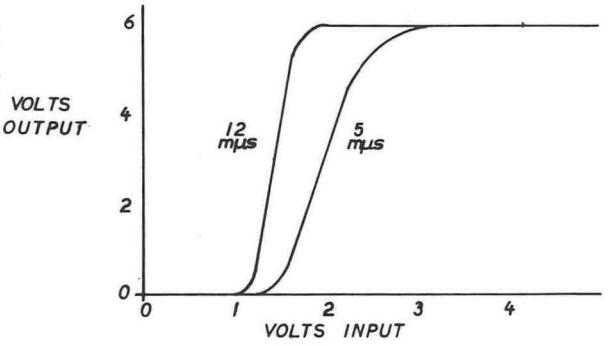

Fig. E11. Measured characteristics of circuit of Fig. E10.

[1] R. L. Garwin, Rev. Sci. Instr. *21*, 569 (1950).

[2] Manufactured by Transitron Electronics Corp. Silicon diodes of comparably small stored charge are available from Transitron and Bell Labs.

[3] Philco type. "Mesa" transistors should also be very useful in circuits of this type, but their current price is rather high to permit the use of many circuits as discussed in this note.

of about 5 mμsec rise and fall (total 10-mμsec duration) were found for signals near the limiting level--larger input pulses produce some stored-charge effect which may stretch the output pulse to 20 mμsec. Once the pulse is over, the circuit is restored and ready for another pulse. The output pulse appears about 10 mμsec after the input pulse.

The limiting-amplifier type of output does not have a sharp threshold like a trigger output stage. Figure E11 shows the output voltage as measured with a cathode-follower probe at the transistor output for various input pulse heights and lengths. Equal pulses were applied to the coincidence-circuit inputs in this test. At input pulse lengths of 5 mμsec or less a deterioration of the input-output characteristic is noticeable. This circuit was tested with both 2N501 and 2N500 transistors and found to be noncritical. The coincidence threshold level can be changed by altering the emitter bias on the transistor, although large reductions of the threshold level result in longer output pulses because of the transistor-stored charge.

Higher-order coincidences may be made by putting in more diodes, but care must be taken to avoid feedthroughs caused by the larger pedestal at the common junction of the diodes. No feedthrough on doubles or triples operation was observed up to the 8-v back-voltage rating of the diodes. With higher-order coincidences, a very large base current is switched to the transistor when a coincidence occurs. This could exceed the transistor ratings. This current can be reduced by passing part of the dc diode currents through another diode paralleling the load resistor for the coincidence diodes, as is done in the Garwin circuit.[1] Normally, the circuit resolving time and threshold are impaired by the extra wiring and

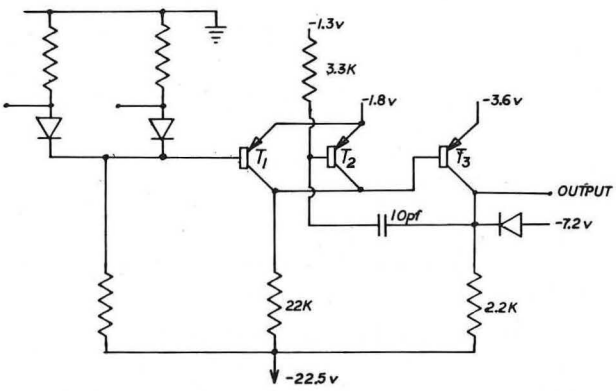

Fig. E12. Negative input coincidence circuit with trigger output.

component capacities when the higher-order coincidences are used that are required in design.

These diode-transistor circuits are limited by the 8-v back-voltage rating of the S570G diodes. If some difficulty is anticipated from occasional large input pulses, several alternatives are available. A diode with higher back-voltage rating (such as the S555G with 15-v rating, but more stored-charge effect) may be used, or a pulse limiter may be employed. The pulse limiters may use biased diodes or transistors.

Triggered Output

When sharper thresholds are desired, a transistor trigger may be connected to the coincidence circuit output. Such trigger circuits may easily be constructed by switching transistors between cutoff and saturation. Typically the pulse length is 100 mμsec and the total dead time is 250 mμsec. These characteristics compare favorably with vacuum tube triggers. With a design that avoids saturating the transistors, faster operation is possible.

A diode coincidence circuit with a univibrator trigger attached is shown in Fig. E12.[4] Transistor T_3 is normally saturated and T_2 is normally cut off. The positive output of T_1 initiates a regenerative action during which the conduction states reverse. The output pulse duration of the trigger is largely determined by the time required to eliminate the stored charge from the base of T_2. The output rise time is about 20 mμsec, and is determined by the 10-ma collector current of T_3, which is switched to the base of T_2 through the 10-μμf feedback condenser. This circuit has several objectionable features. Over short times its triggering threshold width is about 5 mv at the 2-v level, but over long times it is temperature-dependent and is proportional to the supply voltage.[5] There is a short output pulse even for input pulses below the triggering threshold. The output pulse duration may be altered by changing the -1.3-v bias at the base of T_2, but shorter output pulse times are accompanied by an increase in the amplitude of the short feedthrough pulse referred to above. The circuit shown is a compromise which gives an

[4] A group at Princeton University has developed a much better trigger with pulse duration around 35 mμsec. The writer is indebted to Prof. Val Fitch for a discussion of the development work being done at Princeton.

[5] If the bias voltages of Fig. E12 are derived from a single bleeder chain connected across the battery supply, the circuit may be dc bistable and will usually come on in the wrong state.

output pulse of 130 mμsec duration, with a feed-through pulse height about 1/3 of the triggered output. By about 250 mμsec after the initial pulse, the circuit has all dc levels restored and is ready to trigger again at the same level. The delay between the input to the coincidence circuit and the triggered output (at full amplitude) is about 30 mμsec and the trigger pulse timing does not shift relative to the input pulse as the input pulse amplitude is varied near the triggering threshold.

Measured Circuit Characteristics

The coincidence characteristics of the circuit of Fig. E12 are given in Figs. E13 and E14. These characteristics are compared with Garwin circuits of the type currently in use for counting applications at the Chicago cyclotron.[6]

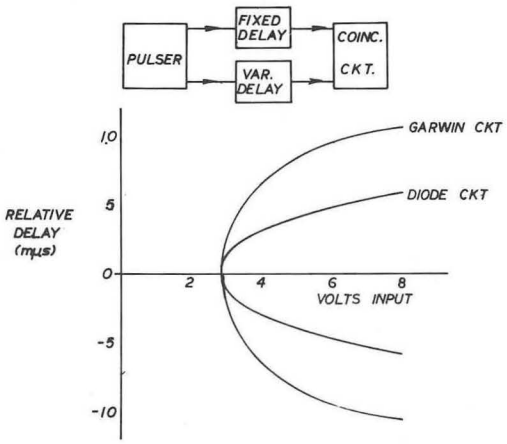

Fig. E13. Coincidence circuit test to determine threshold for equal-amplitude 5-mμsec pulses of improper timing.

In Fig. E13, input pulses of equal height and duration but with variable relative delays were applied to the two inputs of the coincidence circuit. The curves show the threshold for counting. To the right of the curve the circuit counts; to the left of the curve it does not. It is seen that for comparable input pulse lengths (5 mμsec), and for pulse heights far above threshold, the diode circuit has about half the resolving time of the Garwin circuit. For large pulses, the resolving time is essentially the sum of the input pulse lengths plus about 8 or 10 mμsec.

In Fig. E14, 5-mμsec pulses arrive simultaneously at the two coincidence circuit inputs, but with unequal amplitudes. An ideal circuit would have its threshold determined by the smaller of the two pulses. The diode circuit showed no variation in the threshold level of the smaller pulse as the larger pulse varied, within the 10% accuracy of measurement. In the Garwin circuit, variations of a factor of two were observed. This property of the diode circuit makes it useful as a linear gate. E. L. Garwin, of this laboratory, has constructed a linear gate of this type for pulse-height-analysis purposes, and obtained satisfactory linearity at gating times as short as 20 mμsec (Fig. E15).

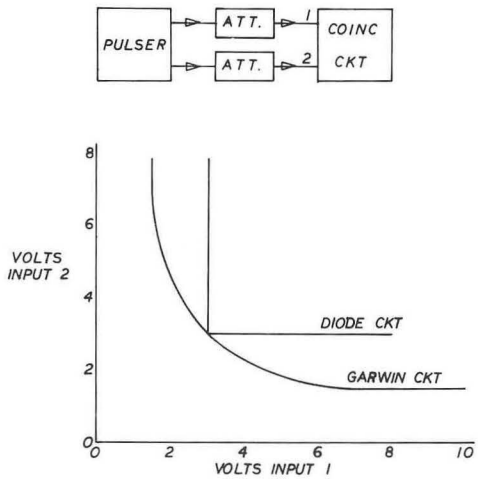

Fig. E14. Coincidence circuit test to determine threshold for properly timed 5-mμsec pulses of unequal amplitude.

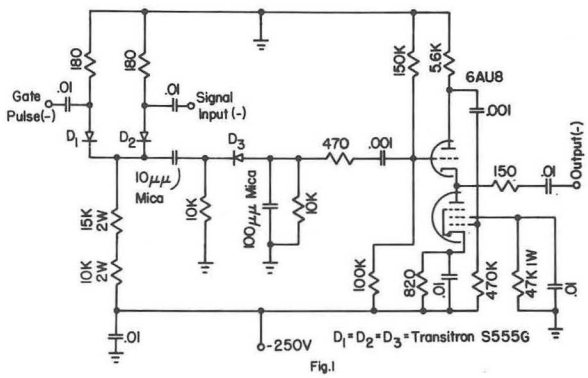

Fig. E15. The circuit diagram for the linear gate. Unless otherwise indicated, condenser values are in μf and resistors are 1/2 watt.

Coincidence Circuit for Positive Pulses

The coincidence circuit can be "turned over" to operate on positive input pulses. Then it is advisable to put in another diode, as shown in Fig. E16, to introduce a threshold. Otherwise the normally conducting transistor is very sensitive

[6] Anderson, Glicksman, and Martin, Proc. Natl. Electronics Conf. 9, 483 (1953); W. Davidson and R. Frank, Rev. Sci. Instr. 27, 15 (1956).

to a pulse at either input terminal, and the circuit feeds through. The circuit shown has a threshold near 4 v, but this may be altered by changing the emitter bias. Figure E17 shows the response of this circuit to various lengths and amplitudes of input pulses. Because the positive-input circuit switches off a conducting transistor, stored charge is more important, and larger variations among individual transistors were found when the circuit was tested with very short input pules (5 mμsec or so). It was found that about 10% of the 2N501's tested (out of 100) required excessive input signals (20% greater than "average" transistors). Transistors not usable for this circuit were usually acceptable for the negative-input circuit.

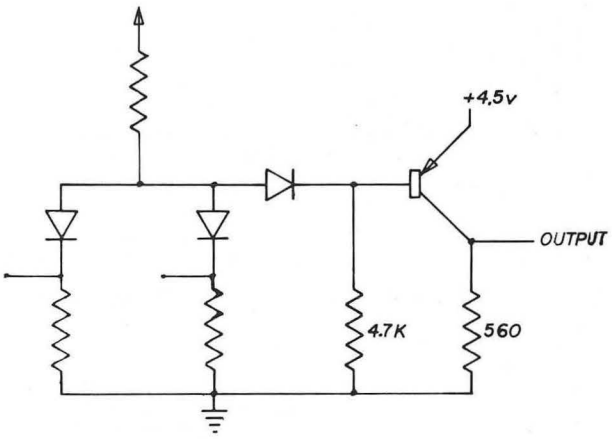

Fig. E16. Coincidence circuit for positive input pulses.

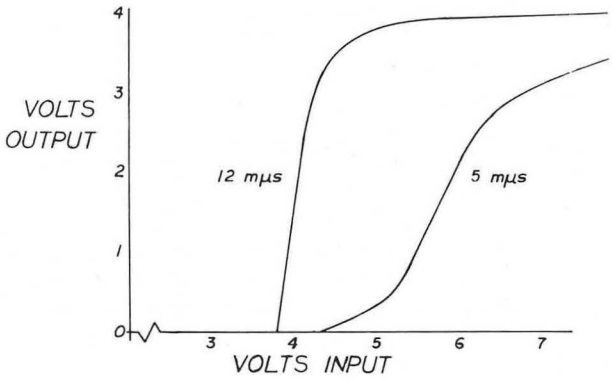

Fig. E17. Measured characteristics of circuit of Fig. E15.

Anticoincidences

An anticoincidence input was made by connecting the collector of a cut off transistor to the common junction of the diodes, as in Fig. E18. The emitter was about 0.1 v above the common junction of the diodes, so that a negative pulse applied to the base of the transistor permitted the transistor to pick up the diode current without changing the voltage at the common junction. This anticoincidence has the problem common to many anticoincidences--for efficient operation to be assured, it is necessary to time the anticoincidence pulse to overlap the signal pulses. Because of stored-charge effects, the inhibiting action of the anticoincidence is not sharply terminated. It stops pulses for times varying up to 10 mμsec after the end of the anticoincidence signal, depending on the amplitudes of these signals. This property may be objectionable in applications in which lifetimes of a few millimicroseconds are being measured, as in pion decays. A type of anticoincidence that avoids this objection is discussed below.

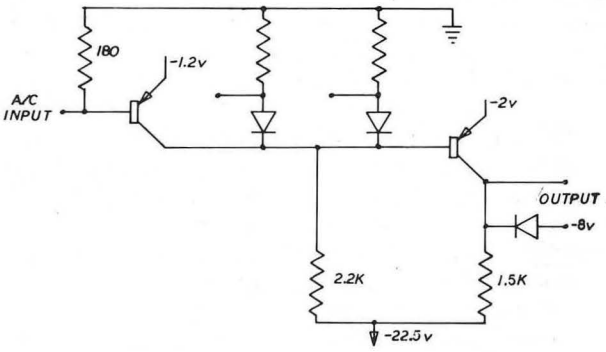

Fig. E18. Coincidence circuit for negative input pulses with anticoincidence input.

Transistor Limiting Amplifiers

Because fast rises are easily obtained with transistors, it would appear that they might be used as limiting amplifiers on counter outputs. In this use, the low power consumption and the lack of cathode glow are additional advantages. Unfortunately, the rise time of transistor amplifiers deteriorates as the load impedance decreases. About 9-mμsec full rises were measured into 100-ohm loads with photomultiplier inputs. The limiting action is good until pulses become large enough to damage the transistor. With the transistor cut off by having its base and emitter normally at the same voltage, there is an input threshold of about 0.1 to 0.2 v. Counter pulses 100 times this threshold were applied without damaging the transistor. However, the transistor conducts by stored charge for times up to 70 mμsec after a 10- to 20-v input pulse. This stored-charge time can be reduced at the cost of higher thresholds by biasing the base farther into

the cutoff region. It is probably best to locate the transistor limiting amplifier at the coincidence circuit, where it may operate into a high impedance load, rather than at the counter, where it must drive a coaxial cable.

Combinations of Circuits

Although the constancy of threshold and slightly better resolving time reported are advantageous, the principal virtue of the present circuits is their simplicity. There are several ways in which this can be used to advantage in fast counting experiments.

First, these circuits can be combined to provide the complete logic of a counting experiment. Typically, rather complicated systems can be built with less effort than normally went into a single general-purpose circuit using vacuum tubes. The circuit of Fig. E10, for example, can be built in about 20 minutes.

Second, these circuits can be combined into much more complicated counting systems than was feasible with vacuum tube circuits. As an example of this, we have considered a counter system in which coincidences between any two of a set of ten counters would be studied for correlations. This requires some 45 doubles circuits, which would be quite complex with vacuum tubes, but which appears feasible with diode and transistor circuits. As another example, anticoincidences may be formed in a way that is likely to require less critical adjustment than the conventional arrangement. Suppose that a counter combination $12\bar{3}$ is required. With simple circuits, it is quite feasible to form coincidences (12) and (123) and to obtain $12\bar{3}$ from the combination (12) $\overline{(123)}$.

Third, these circuits are compact and require little power, so that coincidence circuits can be located at the counters or built into the cabling system. This would reduce the large centralized coincidence circuit and counting racks that are now standard practice.

Discussion

Lynch: What was that 5 millivolts you just referred to, Dr. Miller?

Miller: That was a triggering level width.

Lynch: Could you explain what you mean by that?

Miller: Well, if I were to make a plot of the output volts against the input volts, for a trigger circuit or for an amplifier, it would typically be something like this (Fig. EA). But a trigger circuit employs regeneration to sharpen this very much. Typically a trigger, as you well know, is a go or no-go proposition, but there is some ambiguity in the input pulse height that would make it go, and that is evidently around 5 mv for this circuit.

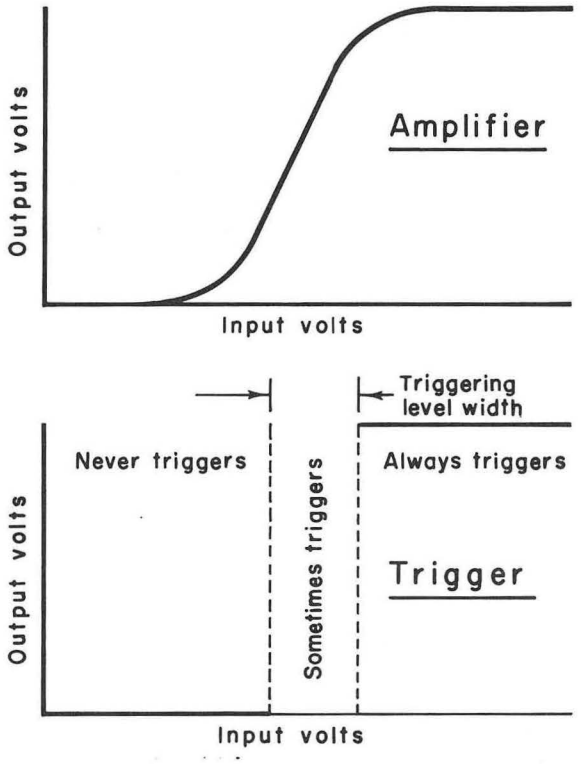

Fig. EA

Lynch: Thank you very much. What is the limit of sensitivity? Could you make the circuit sensitive below 1 or 2 v?

Miller: The circuits that I have shown are sensitive around 1 or 2 v. One could try to bring them lower, but I am afraid there would be trouble with feedthrough in that particular configuration.

Mack: We are constantly looking for fast diodes. We are most interested in units with a dynamic forward resistance lower than 125 ohms and which recover as fast as possible in the reverse direction to an impedance higher than 125 ohms. In the past we have used a number of General Electric Type G-7A germanium point-contact diodes; however, these have not been manufactured for more than a year. Hughes has con-

structed several fast-recovery tubes (HD 2016 and early HD 2130's), but these are no longer available. The fastest unit of which we are aware at present is one of a series manufactured by Qutronics. The Q6-100 can be reverse-biased to 7 v and exhibits a reverse recovery time of the order of 1 mμsec. We find the General Electric of England X-66 diode has approximately the same speed. The several Transitron S-555 and S-570 which we examined were not as fast, nor was the WE 1N696 nearly as fast in our tests. The fastest silicon unit with which we are familiar is the Hewlett-Packard G-111A. They select units for us with forward impedances between 40 and 60 ohms.

Morton: There have been of course a great many experiments on this type of thing, but the gain in counting efficiency is very small. You do gain in counting efficiency if you use the optimum cathode, or somewhat thinner cathode, and come in near a grazing incidence, but of course in almost all real problems that doesn't help you very much because you do have to collect light over a fairly wide angle. In certain special problems it might help to bring the light in at nearly grazing angles, and you would gain a few percent in counting efficiency. And then if there is considerable reflection back out, a mirror can be used to reflect that in again. However, in general, it is a very impractical configuration.

Peterson: I'd like to just put in a word of warning. When you see things like transistors having alpha cutoff at 3,000 Mc, take this with a grain of salt. The experience, now, on computers is that the limiting capacity is no longer the transistor--the internal transistor--but the inevitable shunt capacity of the leads and the case. At the University of Illinois, at the Iliac and particularly in some of the new experiments about a year old, they find that the internal transistor is not at all limiting for them. They find they are right back to the case of vacuum tubes where they have shunt capacities to ground, killing them. I would think that we would do a little better than with tubes, but unless you can do something about the structure, you're going to have trouble getting a unit as effective as a gain-bandwidth product more than 200 or 300 Mc.

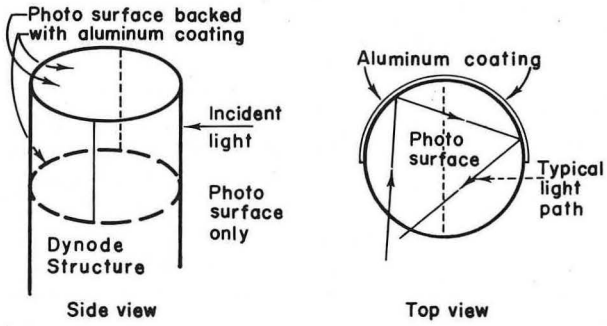

Fig. EB

Parker: I'd like to call attention to a suggestion for a high-quantum-efficiency phototube. See Fig. EB.

In commonly used phototubes such as the 6810, many photons (80 to 90%) do not make useful photoelectrons because the electron travels the wrong way, because it is made too deep in the photolayer to escape, or because the photon does not interact. Increasing the thickness of the layer increases loss due to the second cause; decreasing the thickness increases loss due to the third.

The use of several thin layers of material would reduce loss from both causes. One simple means of doing this with some increase in pulse rise time would be to bring the light in from the side of the tube, aluminize the opposite side and end of the tube, and coat the entire side and end with a photo surface. It is very important to reoptimize the thickness of the photo surface. The new thickness will probably be one-third or less that of an optimized one on a conventional tube.

Most rays will pass through the photosurface four to six times. This is probably as many as can profitably be used, because of attenuation on reflection and in passing through the photosurface.

The increase in rise time should not be excessive for applications in pulse-height analysis (estimated to be a factor of 2 to 4, from observation of collection times of electrons from the sides of a 6810). In Čerenkov counting it can be circumvented by placing a thin scintillator with a conventional phototube ahead of the Čerenkov counter.

Another way to make a high-efficiency tube that might be more flexible would be to coat the inside with the photosurface and later aluminize the outside in any desired pattern.