Title
Spark-Gap-Trigger Amplifier

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Summary

Short over-all time delay, low time jitter, and excellent long-term reliability are among the desirable features designed into a pulse generator that produces a 2-MW output pulse 30 nsec after the application of a 1-V signal at its 50-ohm input connector. The 10-kV output pulse can be used to trigger simultaneously several spark gaps of the type used in spark-chamber pulse modulators.

The 10^8 power gain of the spark-gap-trigger amplifier is achieved by four stages of amplification packaged in a 5-1/4 in. rack-mount chassis that operates directly from a 117-V line. The individual stages, each selected to give minimum time delay for a given power gain at their respective power levels are: avalanche transistors, planar triode, grounded-grid planar triode, and a triggered-spark gap. The techniques used for the last stage, a spark gap triggered by a corona light, are of particular interest since the same techniques are applicable to obtaining short time delays and long-term reliability from the larger spark gaps that the amplifier was designed to trigger.

During 10 months of operation, there have been no failures and no adjustments necessary in any of the seven spark-gap trigger amplifiers used in various spark-chamber experiments at the Lawrence Radiation Laboratory of the University of California (UCLRL) in Berkeley.

I. Introduction

The study of the nuclear events of particle physics has been facilitated by the wide usage of spark chambers to display the trajectories of ionizing particles. Examples of spark chambers currently in use at UCLRL include wide-gap discharge chambers, sonic chambers, 10 in. × 40 in. wire chambers, and multiplate chambers from 1-in. diameter with aluminum foil plates to 6-ft-square chambers with iron plates.

The actual spark-chamber energy source (usually capacitors) varies for each case mentioned above, but a unifying feature of the experimental setups is the use of some "black box" to amplify the logic signals, which may have a level of about 1 V, up to sufficient amplitude to trigger the spark-chamber energy source.[1]

This paper describes a spark-gap trigger amplifier (hereinafter called SGTA) developed to fill this common need of spark-chamber users.

II. Design Aims

A brief discussion of system operation will clarify the reasons for certain design features.

Typically, the logic signals are derived from scintillation detectors whose outputs are compared in coincidence-anticoincidence circuitry, often with the aid of amplifiers and discriminators. The signature of a desired event appears as a pulse of a few volts at some pair of terminals. This pulse forms the input signal to the SGTA. A 1-V sensitivity is quite acceptable and has been chosen as a design input.

Since the size of the spark chambers necessarily varies considerably from one experiment to the next, the output level of the SGTA was chosen by criteria entirely independent of chamber size. It turns out that large spark chambers tend to have large capacitor banks for energy storage and may require several high-power spark gaps to switch the stored energy into the chamber, whereas small chambers may use a small capacitance and a single spark gap. The governing criteria for the output pulse of the SGTA were that it should supply sufficient energy to trigger several high-power gaps simultaneously, and should be compatible with a 50-ohm constant-impedance coaxial system to facilitate transmission of the trigger-pulse energy over shielded cables. Experience with high-powered trigger spark gaps led us to choose 10 kV as the nominal output-pulse voltage for the SGTA.

From discussions with users together with further considerations like the above, we compiled design aims for the SGTA:

1. Voltage levels, impedances, and pulse rates compatible with chamber system requirements.

2. Signal delay of 50 nsec or less, with provision for minimizing extraneous cabling delays.

3. Safety around LH_2 targets.

4. Self-containment for operation from 117-V ac line.

5. Adequate electrical shielding, freedom from spurious triggering, and no pulse feedback to earlier logic stages.

6. Simple operation with a minimum number of adjustments and controls.

A. Voltage and Impedance Levels

The nominal input-signal voltage required is 1 V and the output voltage 10 kV. Input and output impedances of 50 Ω were chosen for compatibility with easily obtainable cables and connectors. Flexibility is provided by a pair of 50-Ω output connectors in parallel; one or both of these may be used as desired. A calculation based on these voltage and impedance levels shows that the nominal power gain of the SGTA is

$$\frac{\text{Power out}}{\text{Power in}} = \frac{(10^4\ \text{V})^2}{25\ \Omega} \bigg/ \frac{1\ \text{V}^2}{50\ \Omega} = 2\times 10^8.$$

B. Pulse Rates

An average pulse rate of 50 pps and a burst rate of 100 pps were selected to be compatible with the dead times of other spark-chamber-system components such as the deionization time of large air gaps, the time for film advance in an optical camera, or the scanning operation in vidicon cameras. Some wire chambers can effectively recycle in less than 10 msec; the present SGTA output stage (an air spark gap) would require modification to accommodate less than 10-msec recycling time. The addition of a few percent CO_2 to the gap atmosphere, together with appropriate recharge-time constants, permits significantly faster recharge time.

C. Signal Delay and Stage Design

In order for one to achieve short signal delay, the necessary power gain of approximately 10^8 is obtained in four stages, each stage selected to give minimum time delay at a given power level.

At the 1-V level, there is no competitor to the avalanche transistor for maximum power gain per unit time delay. On the other hand, the requirement for output power in the neighborhood of two megawatts

$$(10\ \text{kV})^2/50\ \Omega = 2\times 10^6\ \text{W}$$

suggests that at the higher power levels of the intermediate and output stages, one must employ stages of higher individual power level than supplied by avalanche transistors for economy in the number of individual components. In addition, the various stages must exhibit large attenuation to signal passage in the reverse direction. For example, if as much as 1/10,000 of the output power found its way back to the input stage, that stage would "see" a 200-W pulse, an unsafe level for a single avalanche transistor. For the above reasons we designed the stage to provide large attenuation to reverse signal propagation. In the present design, the measured reverse attenuation is 2×10^6 times in voltage (greater than 120 db). The choice of a grounded-grid microwave-triode stage is primarily responsible for the effective isolation.

The stages selected are an avalanche-transistor input stage, an ML-7815 microwave planar-triode driver, an ML-8533 (formerly designated ML-DP-30) grounded-grid stage, and a corona-lamp triggered-gap output stage. Table I lists the gain and time delay of the four stages. Figures 1 and 2 are schematic diagrams of the SGTA. Interior views of the SGTA are shown in Figs. 3 and 4.

1. Avalanche Transistor Stage.

The input stage uses selected avalanche transistors.[2] Two avalanche transistors, stacked in series with collectors fed from a current source, provide a 100-V 1-A positive-polarity grid-voltage pulse to the first planar triode stage, which is normally cut off.

The transistors are triggered by a positive pulse applied to their base-emitter junctions from two secondary windings placed on a ferrite toroid. The two-turn primary winding is completely shielded electrostatically from the two secondary windings to prevent pulses from being launched back into the input circuit at the time the avalanche pulse is produced. In the absence of a trigger pulse, the base-emitter voltage is maintained at zero by the low dc resistance of the secondary winding.

The transistors are selected to have the sum of their avalanche voltages greater than 200 V with their base-emitter junction shorted and collector current adjusted for 100 μA. In addition, the free-running current (i. e., the collector current at which the avalanche is self triggering) is selected to be greater than 500 μA to insure stable operation at elevated temperature. The TI-X-612 transistors, among others, have proved satisfactory.

There have been no failures of avalanche transistors in these circuits over the entire period (more than a year) of development and use of the SGTA.

Table I. Stage gain and delay of trigger amplifier

Stage	Voltage level (V)	Current level (A)	Power gain (db)	Delay time (nsec)
Avalanche transistor (Q_1 - Q_2)	100	1	37	3
Microwave triode (ML-7815)	600	4	14	5
Microwave triode (ML-DP30)	8,000	12	16	7
Triggered gap	10,000	400	15	17
		Totals:	82	32

2. Triode-Amplifier Stages.

The avalanche output signal drives the grid of a grounded cathode-triode stage (ML-7815 planar triode), which in turn drives the grounded-grid second stage (ML-8533 planar triode). The choice of these particular tubes was based on their current and voltage capability, gain bandwidth product, and physical construction, which allows excellent shielding.

The signal to the first grid is a pulse of 100 V at 1 A. (The grid current is 1 A.) The anode of this stage feeds a 4-A pulse to a 4:1 step-down autotransformer to provide a 16-A pulse drive to the second-stage cathode. The 12-A anode current of the 8533 triode charges the anode circuit capacitance. We have measured that the anode voltage falls at a rate of approximately 1 kV/nsec beginning approximately 8 nsec after the application of an input pulse to the avalanche stage. The ML-8533 triode anode signal is coupled to the spark-gap-trigger electrode 1. (See Fig. 1.)

Upon initial application of dc anode voltage, an occasional corona spark ("flash arc") can occur between the anode and grid of the 8533. A 100-Ω resistance in series with the anode and coupling capacitor to the gap electrode limits the energy dissipated in any tube spark to a value of less than 1 mJ. Microscopic examination of the grid wires shows that the tubes are undamaged by sparks of this limited energy. Moreover, the tube and solid-state components are completely protected against damage by transients accidentally introduced into the output line and fed back to the SGTA. Externally introduced transients (up to 200 kV open circuit) merely fire the 1-2 and 2-3 gaps harmlessly.

The ML-8533 planar triode in grounded-grid operation permits almost complete isolation between the high-level spark-gap compartment and the low-level driver compartment. The tube is mounted in a conducting wall separating the two compartments. The grid ring is a continuation of the wall.

The amplitude of positive grid drive and the bias voltage were selected after measurement of positive-grid perveance characteristics for eight tubes. The peak current available to charge the circuit capacitances depends on a combination of space charge and emission limiting, and is therefore somewhat dependent upon cathode temperature. For this reason the heaters of the tubes receive their power from a regulated voltage source.

3. Spark-Gap Stage

The spark gap is a three-electrode gap that is ordinarily operated in an air atmosphere. In brief, in the spark gap operation the trigger electrode over-voltages the gap and a corona lamp[3] initiates an electron avalanche.

In more detail, the triggering sequence of the gap is as follows: Prior to arrival of an input trigger, electrodes 1 and 3 are at ground potential and electrode 2 is at +10 kV. (Gap 1-2 will have been adjusted for a dc breakdown potential of 11.5 kV.) After the arrival of a trigger signal, electrode 1 is pulsed toward a negative 10 kV at a rate of about 1 kV/nsec, the electric field is thereby increased between electrodes 1 and 2. The corona lamp, directed to illuminate electrode 1, is pulsed on to eject photoelectrons from electrode 1. As the current builds up in the 1-2 gap, electrode 1 becomes positive with respect to electrode 3, and an electron avalanche is initiated in the 1-3 gap. Finally, the resistivity of the 1-2 and 1-3 gaps falls with time until the current is limited by the circuit impedances. Note that the 1-2 and 1-3 gaps are in series when carrying the SGTA output current of approximately 400 A.

The absence of any sharp edges or points minimizes the usual erosion problems encountered in some triggered spark-gap designs. No close dimensional tolerances are required to make the gap operate properly. The 1-2 gap is initially adjusted to a 0.125 in. spacing; it can be left for several hundred million pulses without readjustment. The 1-3 gap can be adjusted for minimum time delay while the trigger amplifier is running at a 60-pulse-per-second rate, or it can be adjusted for a 0.054 in. gap and left (again for $>10^8$ pulses) if optimum timing is not required (in the latter case the time delay between the input pulse and output pulse is about 45 nsec rather than the optimum 32-nsec delay). Some erosion must, of course, be expected, but it has been minimized by the proper selection of electrode material. No gap readjustments have been required on any of the seven SGTA's, in use for more than ten months.

a. Electrode Materials. The electrodes could be made of any commonly used electrode materials such as copper, tungsten, brass, or an alloy of tungsten-copper such as Hevimet, Elconite, or Gibsiloy. We have made life tests on electrodes of brass, copper, and Hevimet. The first effect of gap erosion shows up as an increased delay in the output pulse, and this effect can be used as a measure of the quality of an electrode material.

The various tests were made in the same trigger amplifier. Gaps were adjusted so that the delay between the input pulse and the output pulse was 32 nsec at the beginning of each test. After a total of 5×10^6 pulses were run continuously at 60 pps, the time delay had increased to 50 nsec with copper or brass electrodes. Hevimet electrodes had operated for 2×10^8 pulses before the time delay had increased to 50 nsec. In both cases the increased delay was attributed to the erosion of electrode 3. The gap 1-2 was virtually unchanged. The conclusion, then, is that electrode 1, at least, should be constructed of a material such as Hevimet. For simplicity, all electrodes are so constructed.

b. Insulating Supports. The structural layout of the gap keeps all surrounding insulating supports remote from the main blast of the spark (See Figs. 3 and 4). This arrangement minimizes the coating of nonconducting surfaces with conducting debris from the sparks.

c. Corona Lamp. The corona lamp is a version of a design that has been used for phototube testing.[3] A tungsten whisker in contact with a slab of barium titanate is pulsed negative. Field-emitted electrons accelerated from the tungsten excite the atmosphere (in this case, air), which in turn emits light as the excited states decay. The light spectrum has not been measured precisely, but there is sufficient uv to cause emission of several microamperes of photocurrent from metal electrodes of any of the materials mentioned. No glass window is permissible between the light source and the illuminated gap electrode since even quartz windows are found to absorb the hard uv. The lamp therefore operates in the same atmosphere as the gap and is fitted with an internally reflective light pipe that directs the light toward the gap electrodes. The light pipe allows the lamp surface to be placed some distance from the main spark, thus preventing buildup of foreign material on the lamp electrodes.

D. Hydrogen Safety

The output spark gap is completely enclosed in a gas-tight metal compartment. Two fittings are provided for air circulation.

E. Power Supply

One design consideration was that self-contained power supplies would be incorporated to allow the trigger amplifier to operate directly from a 117-V 60-cycle power line. A 10-kV 1-mA Cockcroft-Walton voltage-multiplier power supply provides all dc voltages from appropriate taps (i. e., +10 kV for the spark gap and the anode of the ML-8533 triode, +2500 V for the anode of the ML-7815 triode, +400 V for the tube bias, and -400 V for the avalanche transistors.)

To supply the required no-load-to-full-load regulation in simple fashion, the hv stack is driven both at the low-voltage end and at a position about two thirds of the way up the stack by an epoxy-insulated transformer that has two separate secondary windings. The primary of the transformer is driven by a 14.5-kc square wave from an oscillator-amplifier combination that operates from a dc 26.5-volt supply. The (0 to 1)-ma load regulation at the 10-kV tap on the stack is within 5% for a constant 26.5-volt supply to the oscillator-amplifier.

A simple bridge rectifier and capacitor filter provide the 26.5-dc voltage. The ac voltage for the bridge and the filament power come from a Sola constant-voltage transformer, which maintains the dc and filament voltages within 3% of the nominal values for all normal load variations and for line voltages of 90 to 130 V ac.

F. Cabling and Shielding

Since the SGTA was designed to be operated in a constant-impedance system, a 50-Ω cable should connect the SGTA and the spark-chamber energy source. To take full advantage of the excellent shielding of the SGTA, the connecting cable should be an electrically tight 50-Ω variety such as the Foam V Heliax made by the Andrew Corporation. A modified HN-type cable connector has been designed for use with the cable, and is shown in use with a wide-gap chamber in reference 1.

The shielded input transformer and the grid-separation triode stage together prevent feedback of energy into the input trigger line when the 10-kV output pulse is generated. A spurious signal voltage of less than 5 mV appears on the 1-V input-signal line. Thus there is no danger of falsely triggering devices that may be connected to the input line.

The 117-V power line passes through copper tubing to the primary winding on the Sola constant-voltage transformer. Electrostatic shields placed inside the transformer shells reduce the capacitance between the primary winding and all other windings to less than 5×10^{-6} pF. The amplitude of spurious signal coupled into the power line is below 1 mV.

A shielding evaluation of the SGTA driving the foam Heliax cable shows that spurious signals external to the cable or amplifier are not greater than 5 mV, including those from power-line wires, monitor connections, and external-metal-panel surfaces.

The large attenuation not only prevents spurious signals from within the SGTA from getting out, but it allows the SGTA to operate in an electrically noisy environment without producing false triggering of the input circuit. Thus it has been possible to operate a set of SGTA's, each firing a spark chamber in a time-delayed sequence, with no cross-talk problem.

III. Operation

To operate the SGTA, it is necessary only to plug it into a 117-V ac 60-cycle power line and turn on the front panel switch. No adjustments are necessary.

Figure 5 shows the voltage waveforms present at the input, the two monitors, and the output. The input trigger is larger than 1 V in order that it may show clearly on the trace. The delays are the same for a 1-V input trigger. All impedance levels are 50 Ω. The photographs are multiple exposures taken with the SGTA running at a rate of 60 pps. The time delay from the input pulse to the half-amplitude point on the output pulse is approximately 40 nsec.

The chassis of the SGTA is built in two separable sections. The trigger amplifier and high-voltage power supply are in an aluminum box (section 1), which normally plugs into a front panel rack-mountable chassis that contains the low-voltage power supplies (section 2).

The aluminum box of section 1, which contains the air spark gap, has been made gas tight. Two gas-line fittings in the spark-gap compartment are left vented to the atmosphere to allow contaminated air to circulate away from the spark gap. If the SGTA is used near an LH_2 target, air is circulated through the spark-gap compartment at the rate of 1 to 10 cc/min.

When shortest possible system delays are desired, the amplifier chassis is removed from the front panel and placed near the spark-chamber energy source, thus eliminating extraneous cabling delays. A 25-foot extension cable connects power between the two sections, making it possible to mount the front panel in an accessible location outside a target area.

Figure 6 shows the SGTA being used in the Chamberlain Group's Σ-parity experiment at the Bevatron.

REFERENCES

1. Quentin A. Kerns, "Spark-Chamber Pulse Modulators," Lawrence Radiation Laboratory Report UCRL-10887, June 1963 (unpublished).
2. Harold W. Miller and Quentin A. Kerns, "Transistors for Avalanche-Mode Operation," Rev. Sci. Instr. 33, 887 (1962).
3. Thomas G. Innes and Quentin A. Kerns, "A Pulsed Nanosecond Light Source," Western Electronic Show and Convention Record, Aug. 22-25, 1961.

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

Figure Captions

Fig. 1. SGTA, amplifier section and hv power supply, schematic diagram.

Fig. 2. SGTA, lv power supply, schematic diagram.

Fig. 3. SGTA - top view, with covers removed.

Fig. 4. SGTA - bottom view, with covers removed.

Fig. 5. SGTA - connector voltage wave forms.
Horizontal sweeps: 20 nsec/div
Pulse rate: 60 pps

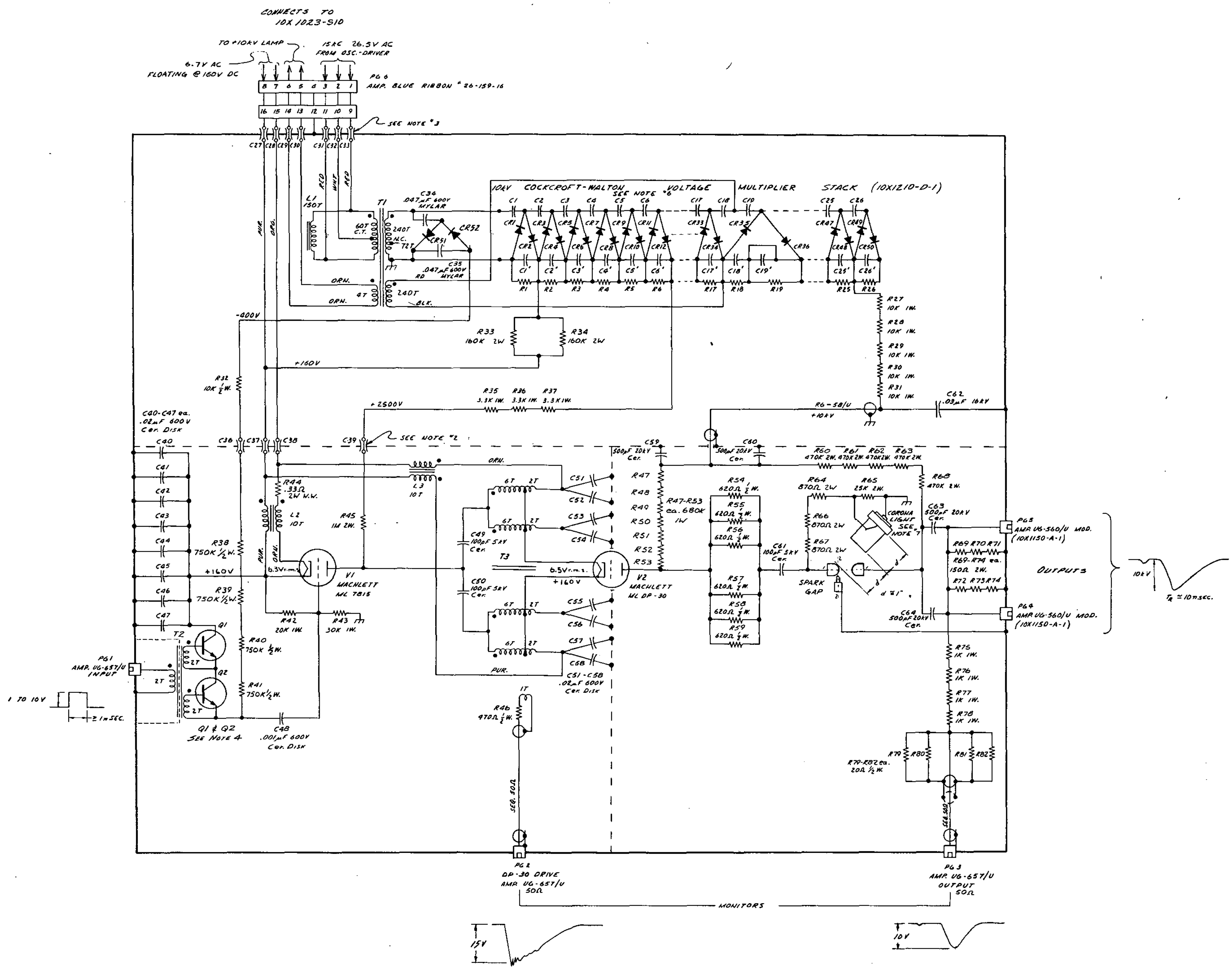
(a). Input trigger
Vert sens: 10 V/div

(b). PG-2 monitor:
Vert sens: 10 V/div

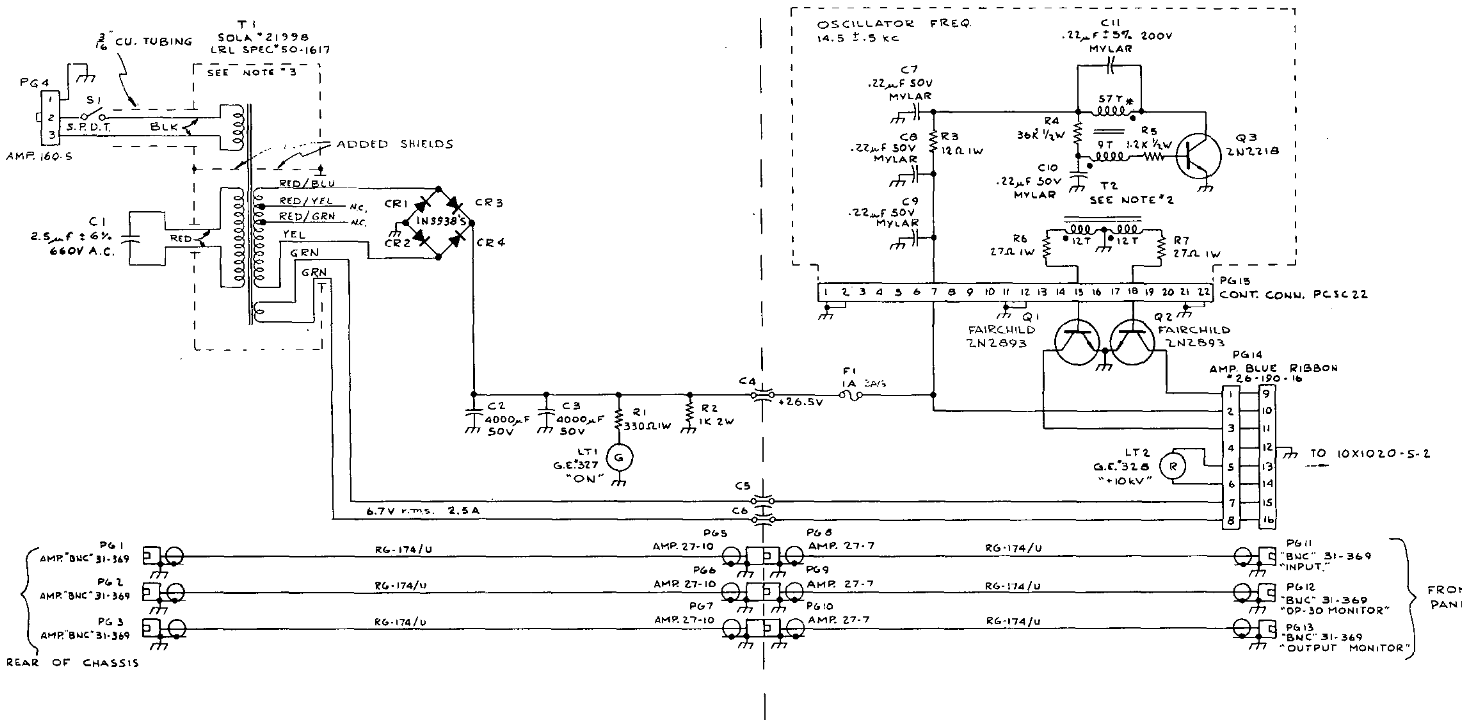
(c). PG-3 monitor:
Vert sens: 10 V/div

(d). Output pulse:
Vert sens: 4 kV/div

Fig. 6. View of target area in a Σ-parity experiment.

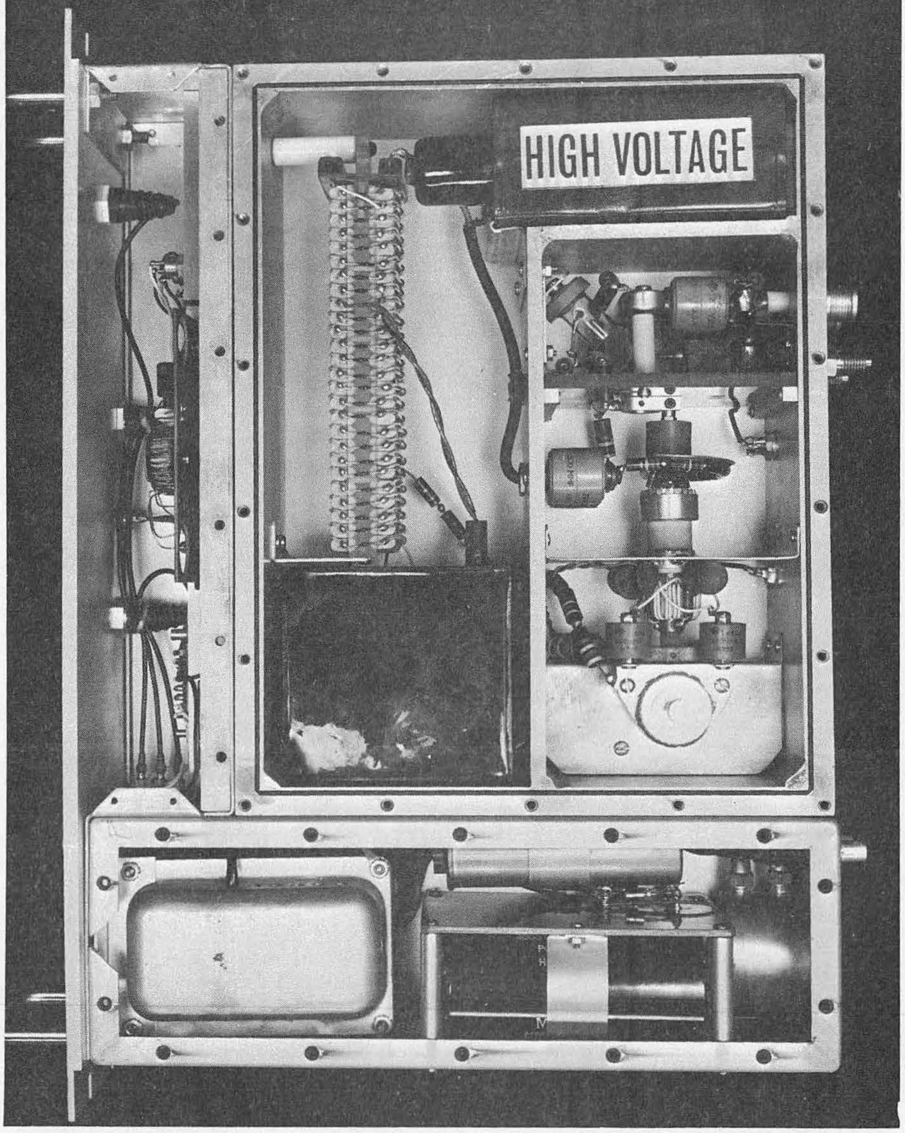

CONNECTS TO
10X 1023-S10
TO +10KV LAMP
6.7V AC
FLOATING @ 160V DC
15KC 26.5V AC
FROM OSC.-DRIVER
PG 6
AMP. BLUE RIBBON # 26-159-16
SEE NOTE #3
10KV COCKCROFT-WALTON VOLTAGE MULTIPLIER STACK (10X1210-D-1)
SEE NOTE #6
.047μF 600V MYLAR
-400V
+160V
+2500V
SEE NOTE #2
R33 160K 2W
R34 160K 2W
R35 3.3K 1W.
R36 3.3K 1W.
R37 3.3K 1W.
R27 10K 1W.
R28 10K 1W.
R29 10K 1W.
R30 10K 1W.
R31 10K 1W.
C62 .03μF 16KV
RG-58/U
+10KV
C40-C47 ea. .02μF 600V Cer. Disk
R32 10K ½W.
R38 750K ½W.
R39 750K ½W.
R40 750K ½W.
R41 750K ½W.
R44 .33Ω 2W W.W.
R45 1M 2W.
R42 20K 1W.
R43 30K 1W.
V1 MACHLETT ML 7815
V2 MACHLETT ML DP-30
6.3Vr.m.s.
6.5Vr.m.s.
C49 100pF 5KV Cer.
C50 100pF 5KV Cer.
C51-C58 .02μF 600V Cer. Disk
R47-R53 ea. 680K 1W
C59 500pF 20KV Cer.
C60 500pF 20KV Cer.
R60 R61 R62 R63 470K 2W.
R54 620Ω ½W.
R64 870Ω 2W
R65 25K 2W.
R66 870Ω 2W
R67 870Ω 2W
R68 470K 2W.
CORONA LIGHT SEE NOTE #7
C61 100pF 5KV Cer.
C63 500pF 20KV Cer.
C64 500pF 20KV Cer.
SPARK GAP
PG5 AMP. UG-560/U MOD. (10X1150-A-1)
PG4 AMP. UG-560/U MOD. (10X1150-A-1)
R69-R74 ea. 150Ω 2W.
OUTPUTS
10KV
T_R ≈ 10nsec.
R75 1K 1W.
R76 1K 1W.
R77 1K 1W.
R78 1K 1W.
R79-R82 ea. 20Ω ½W.
PG1 AMP. UG-657/U INPUT
1 TO 10V
≥ 1nSEC.
Q1 & Q2 SEE NOTE 4
C48 .001μF 600V Cer. Disk
R46 470Ω ½W.
SER. 50Ω
PG2 DP-30 DRIVE AMP. UG-657/U 50Ω
PG3 AMP. UG-657/U OUTPUT 50Ω
MONITORS
15V
10V

MUB-4357



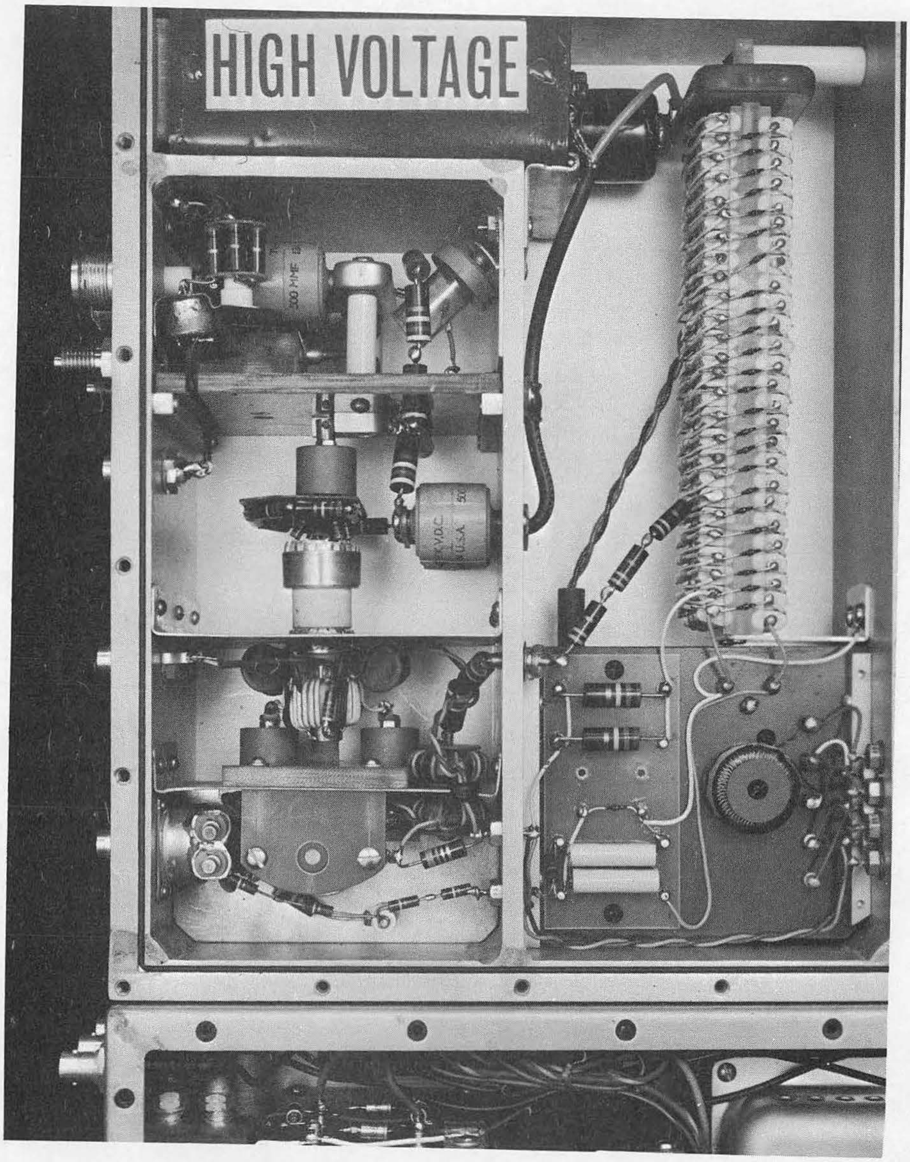
MUB-4358

Fig. 2



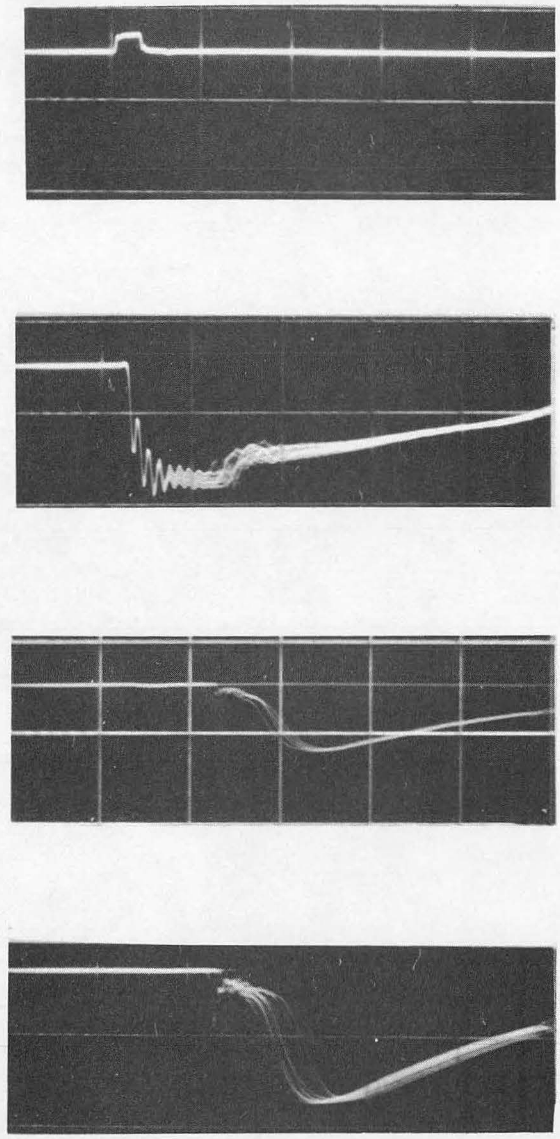
ZN-4538

Fig. 3



ZN-4540

Fig. 4



A

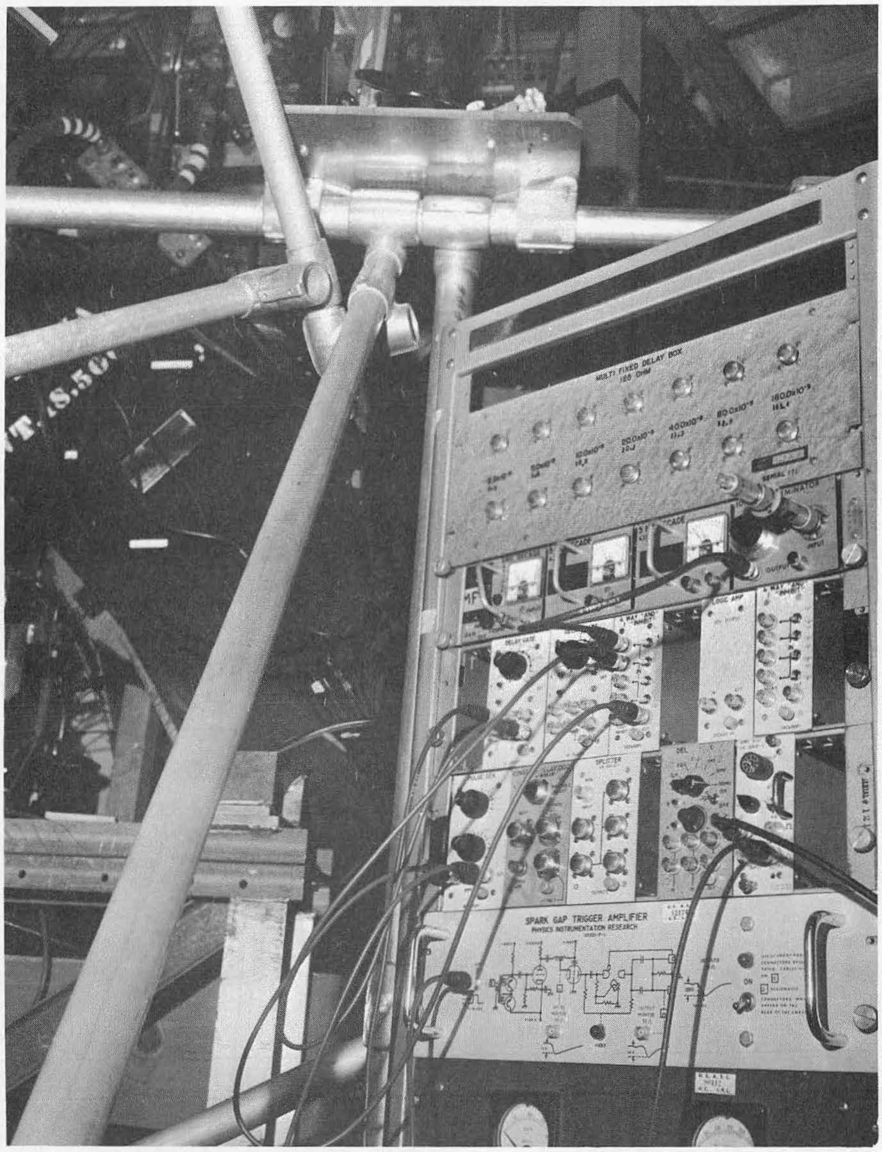
B

C

D

ZN-4541

Fig. 5


MULTI FIXED DELAY BOX
SPARK GAP TRIGGER AMPLIFIER
PHYSICS INSTRUMENTATION RESEARCH

ZN-4542

Fig. 6