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DEVELOPMENT OF A HIGH-ENERGY CROWBAR FOR THE LOS ALAMOS FREE-ELECTRON LASER*

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A 135-kV, 2.5-µs crowbar has been developed to protect the TH2095A klystrons used on the Los Alamos free-electron laser. The klystron power supply consists of a 135-kV, 8.75-µF capacitor bank with a stored energy of approximately 80 kJ. The TH2095A specifications require that the dissipated energy in a klystron arc be limited to less than 10 J. The crowbar design is based upon a series stack of pressurized spark gaps immersed in an oil tank. The spark gaps are triggered by an SCR-switched high-voltage trigger transformer. Input triggers are provided by current-monitoring transformers. The following currents are sensed for input triggers: total system current, integrated system current (long pulse sensing), cathode current, and modulator-anode current. Trigger levels are set to approximately 150% of nominal current levels. Unique features of this design are its modulator-anode trigger, noise immunity, and ability to print out the energy dissipated in the klystron arc. Typical operation of this system limits the energy dissipated in an arc to less than 2 J. This paper describes the original design requirements, mechanical layout and fabrication, main trigger circuit design, modulator-anode trigger design, noise immunity circuit, integrated energy monitor, diagnostics, and recent developments. Performance data are also included.

1. Introduction

The Los Alamos free-electron laser (FEL) experiment uses two 5.5-MW TH2095A klystrons to supply rf power to its accelerators (see fig. 1). These modulating-anode (mod-anode) klystrons were chosen mainly to satisfy the experiment's long pulse-width requirements [1]. The TH2095A klystron is, however, extremely sensitive to internal arcs. The manufacturer has recommended that the

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energy dissipated in an internal arc be limited to 10 J. To meet this internal-arc energy limit required that we develop a crowbar system capable of rapidly and reliably sensing arcing conditions and safely dumping the stored energy before it could be dissipated in the arc. In the following sections we will discuss the techniques we have employed to accomplish this.

2. Crowbar system

The heart of the FEL crowbar system consists of a set of pressurized spark gaps. These gaps were chosen because of their voltage and current ratings, lifetime, reliability, speed of discharge, small size, and relatively quiet operation. As shown in fig. 2, two triggered gaps (E1 and E2) are wired in parallel to improve the reliability of the system. Both E1 and E2 are triggered during a crowbar, thus assuring that one or the other will fire. These triggered gaps are wired in series with a third 45-kV overvoltage spark gap (E3). The triggered gaps have a self-breakdown voltage of 120 kV. Their use in series with E3 allows the crowbar to operate up to 165 kV. A voltage divider consisting of R32 and R33 maintains the proper voltage levels across each spark gap before firing. The two RC networks (R34 & C17 and R35, C18, & C19) are used to maintain the current across the spark gaps during the discharge period. The RC networks (R15 & C8 and R31 & C16) on the triggered spark gaps are recommended by the factory for optimum firing. Two 70:1 high-voltage trigger transformers (T1 and T2) are used to fire the triggered spark gaps. The primary of either T1 or T2 is driven to 350 V by trigger card 1 or 2 when an arc signal is sensed. The secondary of the trigger transformer then delivers a pulse of approximately 25 kV to the trigger electrode of E1 or E2. When E1 or E2 is triggered, the voltage across E3 jumps to the full bank voltage, exceeding its breakdown voltage so that its gap also fires. This sequence thus shorts the capacitor bank to ground.

Because gap E3 requires 45 kV to break down, the crowbar will not work when the operating voltage is much less than 50 kV. To alleviate this problem, a gap-shorting relay has been added to the circuit, in parallel with E3. A comparator circuit monitors the bank voltage. If this voltage is less than 80 kV, gap E3 is shorted out by relay K6. This condition applies the full supply voltage across the triggered gaps and allows the crowbar to operate, as intended, at voltages less than

135 kV but greater than 5 kV. An additional relay, K5, completely shorts the crowbar to ground during maintenance or personnel-entry periods.

The trigger transformers, spark gaps, and RC networks are all immersed in oil in a large metal tank. Initially the crowbar often arced because of contaminated oil and insufficient component spacing. These problems were eliminated by enlarging the tank and by adding an oil-filtration system. The new system uses Lexan insulating rods to separate the corona rings upon which the spark gaps are mounted. Lexan is very strong and has good high-voltage qualities.

The old crowbar system took about 3 to 4 μs to fire (measured from the time the klystron current exceeds the trigger level to the time at which the crowbar begins to discharge the capacitor bank). Trigger circuits were added to the new system to reduce this firing time to less than 2.5 μs and are discussed below.

3. Trigger circuits

Trigger signal inputs for the crowbar are provided by six separate current-sensing transformers. The cathode (at A1 and B1 of fig. 1) and mod-anode (at A2 and B2) currents are sensed in each modulator tank. If any one of these four currents exceeds 150% of its nominal value, the crowbar system will fire. Two additional current transformers are used (at C and D) to sense the total return current from the modulator tanks. One of these (C) is used as a total current trigger source. The other transformer's output (D) is integrated over time to detect and trigger on unusually long pulses or on extra pulses. The outputs of the cathode current and total current transformers are sent directly to trigger cards 1 and 2 (fig. 2). The mod-anode circuit must go through a special buffering circuit before going to the standard crowbar trigger. This circuit will be discussed later.

The trigger driver consists of a high-voltage silicon-controlled rectifier (SCR) and a voltage divider network (fig. 3). The input signal is divided in half by R23 and R39 and applied directly to the input of the SCR. A bias network consisting of R24 and CR12 is used to bias the gate to −0.5 V, which helps to keep any input noise from triggering the SCR. Diode CR13 protects the bias supply from reverse voltage spikes. When the SCR fires, C15 discharges through SCR2 and the primary of T2 and produces a peak primary pulse of about 350 V. When the SCR turns off, C15 is recharged through R16 and the primary of T2. Diodes CR14 and CR15 protect the SCR from high-voltage kickback from the secondary of T2; R28 and R29 are bleeder resistors for C15 when the card is removed from service. All of the input signals are applied to the SCR in the same manner, but the mod-anode signal must be conditioned first.

4. Mod-anode trigger circuit

A typical mod-anode current waveform is shown in fig. 4. The negative spike at the beginning is caused by capacitance in the modulator circuit. To have reliable triggering, it is necessary to delay the trigger circuit so that it ignores the spike and monitors only the flat region of the current waveform. Fig. 5 shows a block diagram of the mod-anode trigger circuit that accomplishes this.

The current pulse from the mod-anode current transformer is connected to an amplifier by an analog switch. The gate to the analog switch is delayed by 20-30 μs so that the trigger circuit ignores the negative spike on the mod-anode current waveform. The other modulator trigger sources are adequate to protect the system during this short time interval. The amplified mod-anode current is compared to both positive and negative reference set points. Should the current exceed either set point, the comparator fires the SCR on one of the main trigger cards. This circuit has proved to be very reliable and quite sensitive to internal mod-anode arcs.

5. Tests and diagnostics

A number of diagnostic tools are used to measure the performance of the crowbar system. Each morning all of the trigger inputs are tested for operation under simulated working conditions. The capacitor bank is shorted to ground by a large high-voltage switch. The current through the switch is sensed by a current transformer identical to those used elsewhere in the system, and this signal is used to trigger each of the crowbar inputs, one at a time.

Each time the crowbar fires in normal operation, the return current to the capacitor bank is sensed by a current transformer. This current pulse is integrated over time with a simple RC integrator interfaced to an HP-85B computer and recorder. The integrated signal is used to compute the total energy discharged in the arc and is then printed out by the system. The threshold level of the monitor is set to print all energies above 0.6 J. Energy levels for typical crowbars range from 0.7 to

1.2 J. Worst-case energies are in the 3-J range. These usually occur when the spark gaps have reached their lifetime limit.

The signal from a current transformer on the ground lead of the high-voltage switch is used to measure the peak capacitor bank current during crowbar. This signal is displayed on an analog storage scope. A typical capacitor bank current waveform is shown in fig. 6. Note that the crowbar fires in less than 2.5 μs.

6. Conclusion

A fast, reliable crowbar has been designed and has been in use to protect the TH2095A klystrons used at the Los Alamos FEL facility. The limit imposed by the manufacturer on internal arc energy required that some unique triggering techniques be developed. The result is a system that has worked within these limits consistently and reliably for more than two years.

Acknowledgments

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Reference

[1] R.W. Warren, J.S. Fraser, W.E. Stein, J.G. Winston, T.A. Swann, A. Lumpkin R.L. Sheffield, J.E. Sollid, B.E. Newnam, C.A. Brau, and J.M. Watson, "The Los Alamos free-electron laser oscillator experiment: plans and present status," *Free-Electron Generators of Coherent Radiation*, Charles A. Brau, Stephen F. Jacobs, Marlan O. Scully, Eds., Proc. SPIE 453, 130-136 (1984).

Figure Captions

Fig. 1. Block diagram of the FEL rf system.

Fig. 2. Schematic diagram of the crowbar system spark-gap circuitry. Two spark gaps are wired in parallel to enhance reliability.

Fig. 3. Schematic diagram of the trigger driver circuit.

Fig. 4. Mod-anode current as a function of time.

Fig. 5. Block diagram of the mod-anode trigger circuit. Two comparators are used for dual polarity triggering.

Fig. 6. Capacitor bank current as a function of time. The crowbar fires approximately 2.5 μs after the current is initiated.

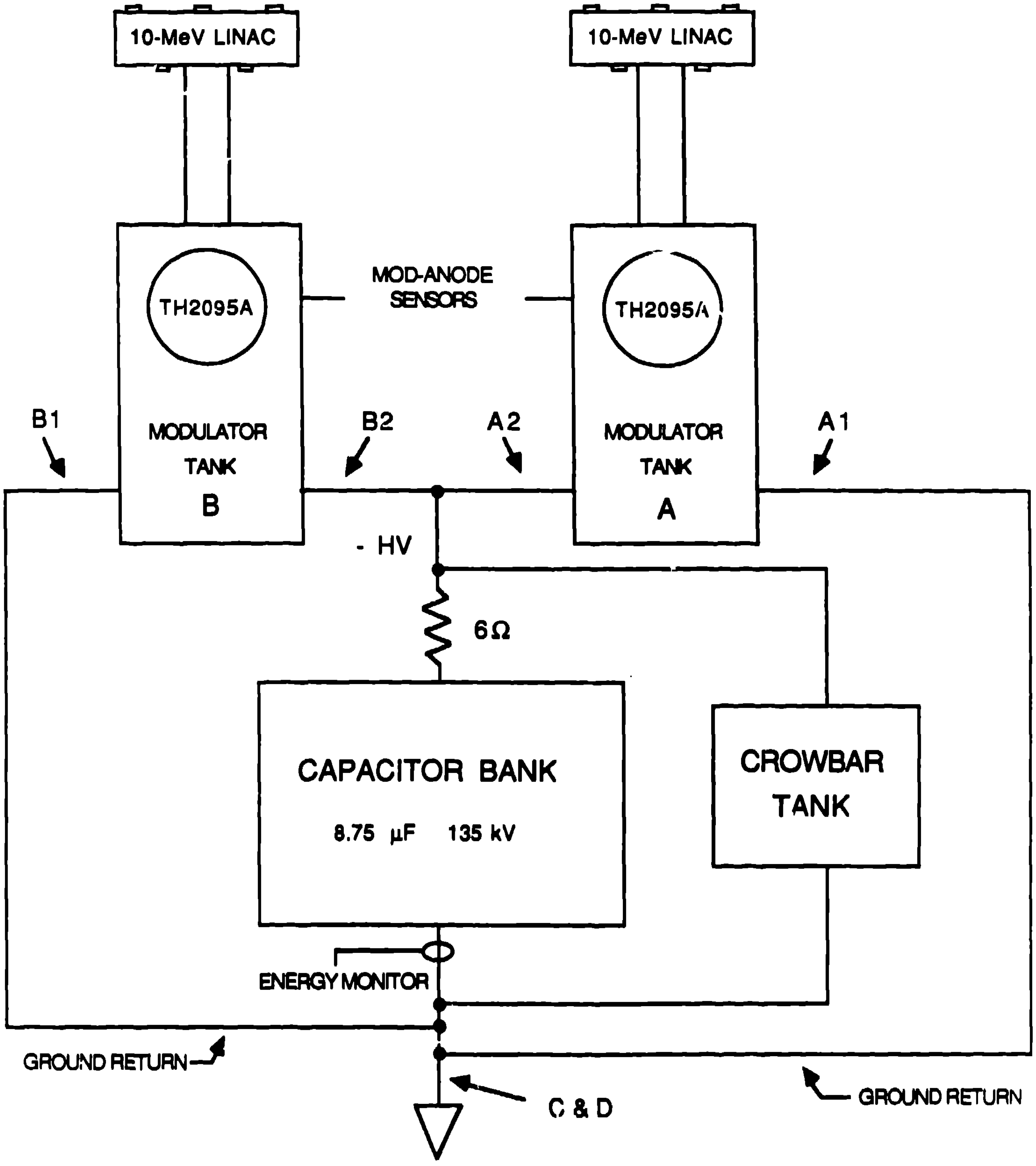
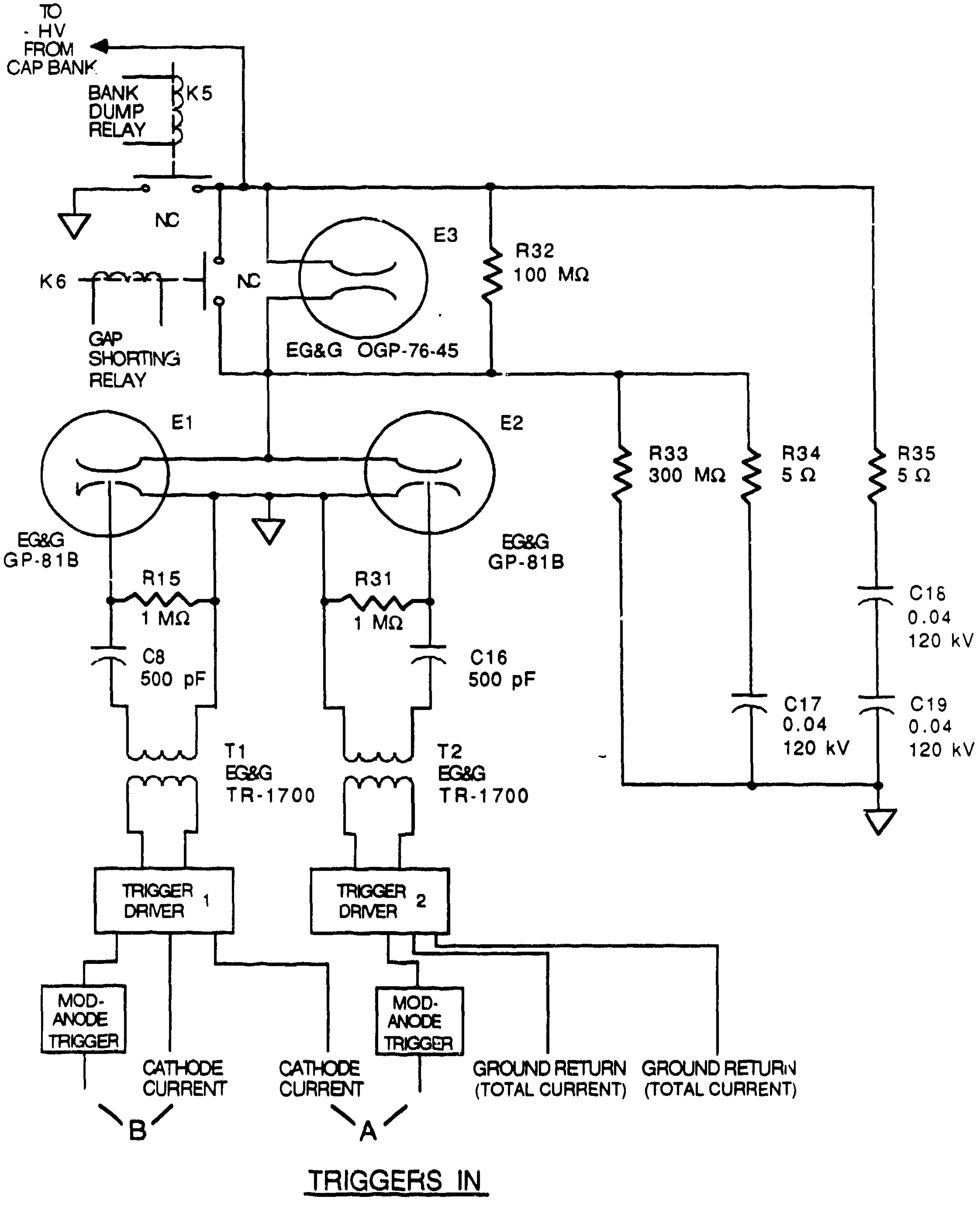

10-MeV LINAC
10-MeV LINAC
TH2095A
TH2095A
MOD-ANODE SENSORS
B1
MODULATOR TANK B
B2
A2
MODULATOR TANK A
A1
- HV
6Ω
CAPACITOR BANK
8.75 µF 135 kV
CROWBAR TANK
ENERGY MONITOR
GROUND RETURN
C & D
GROUND RETURN

FIG. 1



TO
- HV
FROM
CAP BANK
BANK
DUMP
RELAY
K5
NC
K6
NC
GAP
SHORTING
RELAY
E3
EG&G OGP-76-45
R32
100 MΩ
E1
E2
EG&G
GP-81B
EG&G
GP-81B
R33
300 MΩ
R34
5 Ω
R35
5 Ω
R15
1 MΩ
R31
1 MΩ
C8
500 pF
C16
500 pF
C18
0.04
120 kV
C17
0.04
120 kV
C19
0.04
120 kV
T1
EG&G
TR-1700
T2
EG&G
TR-1700
TRIGGER
DRIVER
1
TRIGGER
DRIVER
2
MOD-
ANODE
TRIGGER
MOD-
ANODE
TRIGGER
CATHODE
CURRENT
CATHODE
CURRENT
GROUND RETURN
(TOTAL CURRENT)
GROUND RETURN
(TOTAL CURRENT)
B
A
TRIGGERS IN

FIG. 2

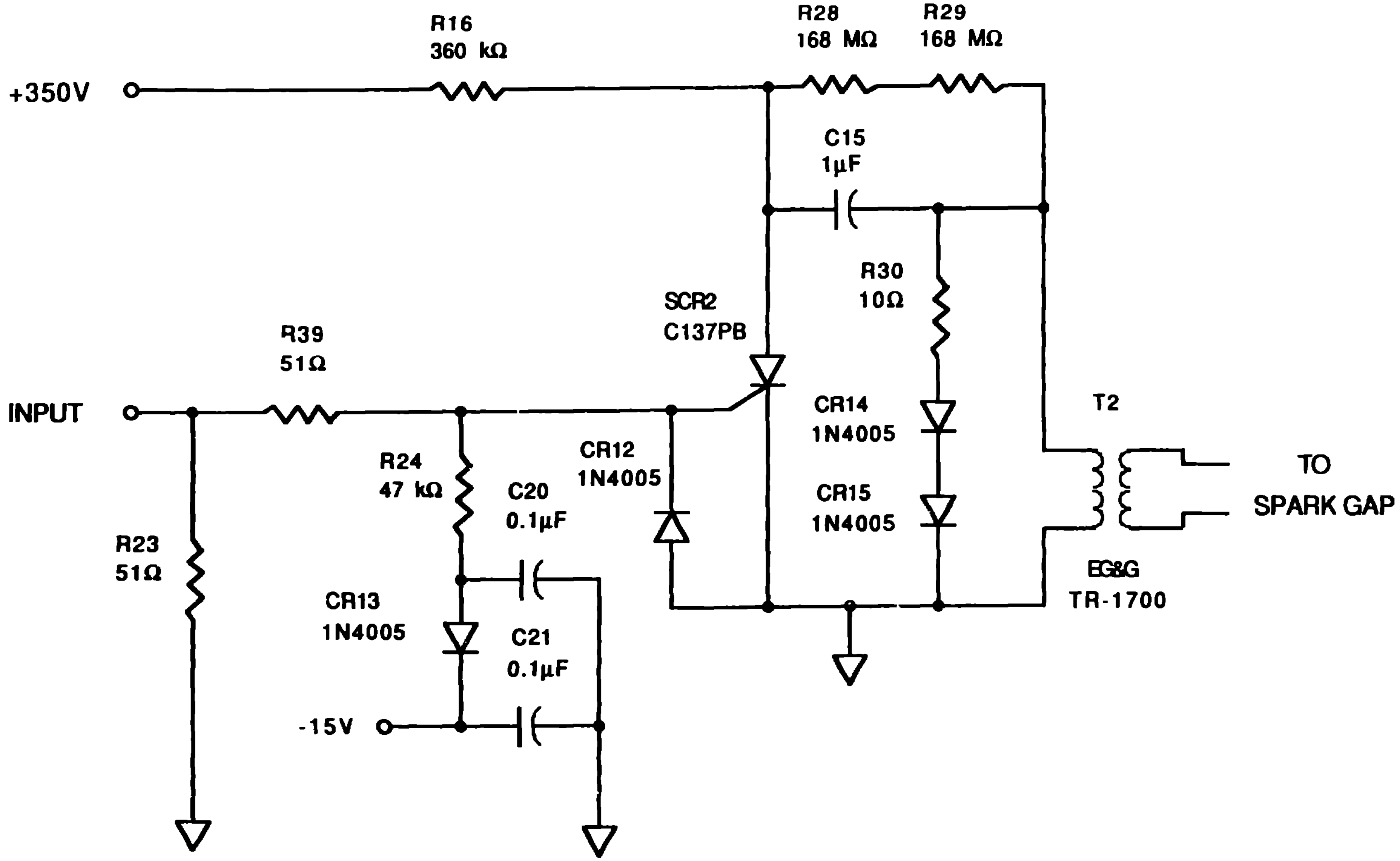
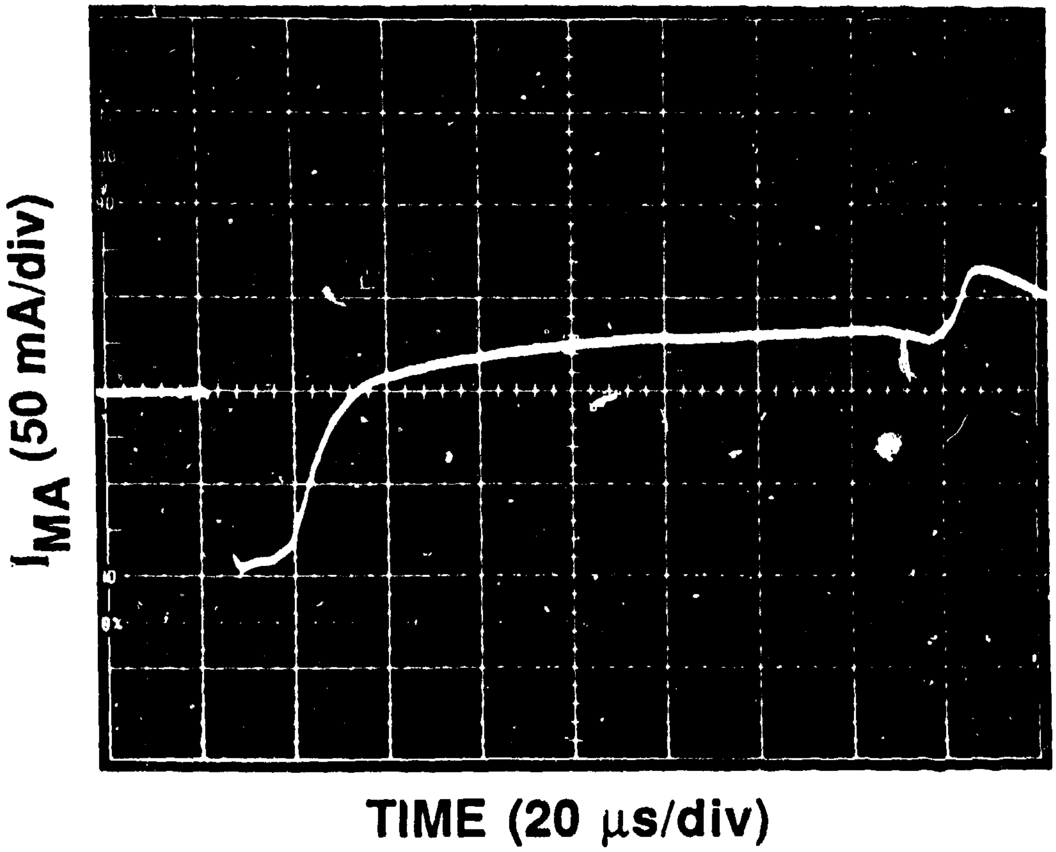

R16
360 kΩ
R28
168 MΩ
R29
168 MΩ
+350V
C15
1µF
R30
10Ω
SCR2
C137PB
R39
51Ω
INPUT
CR14
1N4005
T2
R24
47 kΩ
CR12
1N4005
C20
0.1µF
CR15
1N4005
TO
SPARK GAP
R23
51Ω
EG&G
TR-1700
CR13
1N4005
C21
0.1µF
-15V

FIG. 3


I_{MA} (50 mA/div)
TIME (20 μs/div)

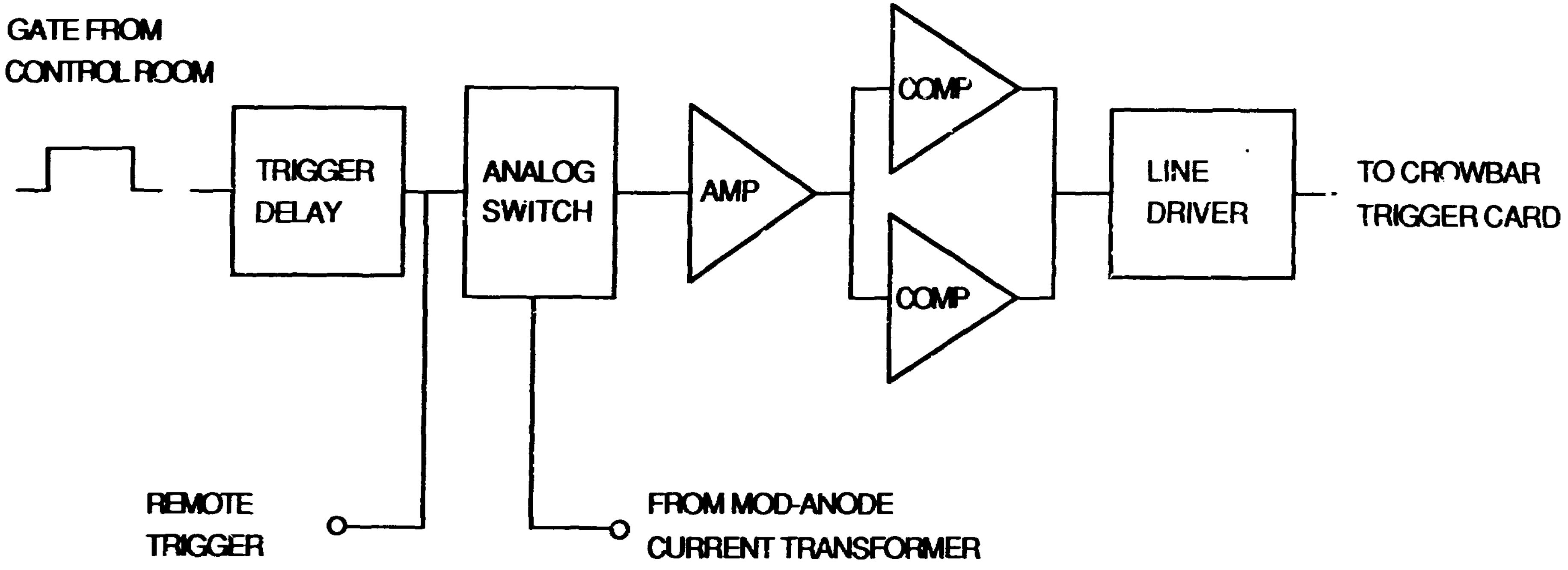
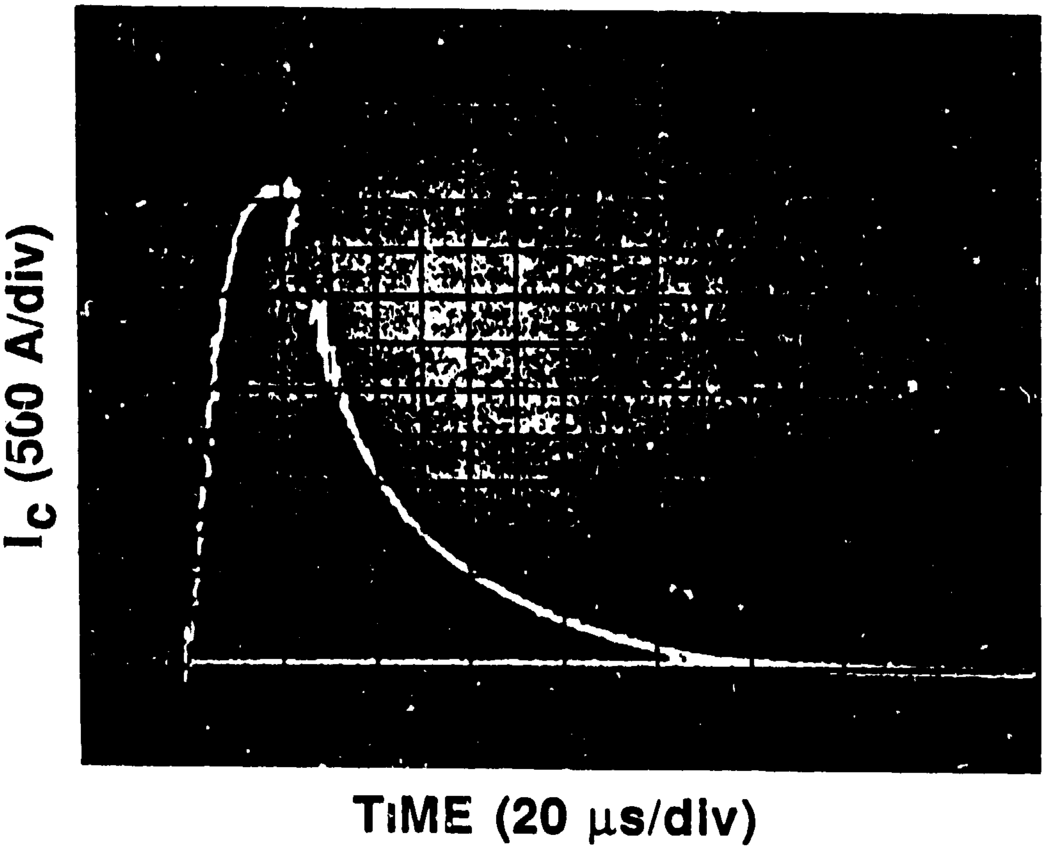

GATE FROM
CONTROL ROOM
TRIGGER
DELAY
ANALOG
SWITCH
AMP
COMP
COMP
LINE
DRIVER
TO CROWBAR
TRIGGER CARD
REMOTE
TRIGGER
FROM MOD-ANODE
CURRENT TRANSFORMER

FIG. 5


I_c (500 A/div)
TIME (20 μs/div)