SLAC-PUB-53
October 1964

PULSED BENDING MAGNET SYSTEM FOR THE STANFORD TWO-MILE ACCELERATOR*

J. L. Cole and J. J. Muray
Stanford Linear Accelerator Center, Stanford University, Stanford, California

Abstract

The electron beam from the Stanford two-mile linear accelerator is analyzed by a high-quality magnetic deflection system in the beam switchyard. The first magnet element in this system is a pulsed switching magnet capable of switching beams of different energies and intensities to either transport system on a pulse-to-pulse basis. This magnet actually consists of five one-meter sections and is powered by pulsed high-voltage supplies (modulators). Each magnet section is excited with two modulators because it must pulse in either polarity in order to switch the beam left or right; the pulse height should be continuously variable to accommodate any beam energy. The magnetic field in these magnets rises sinusoidally 360 times a second and has a peak value at 1700 gauss.

In this paper the optical properties of pulsed magnet will be discussed briefly. Detailed descriptions of the pulsed magnet modulators, the instrumentation for the magnet, and the test results will be given. The problems connected with high-power switching at high repetition rates will be discussed.

General

The electron beam from the Stanford two-mile linear accelerator is analyzed by a high quality magnetic deflection system in the beam switchyard. The basic elements of the magnetic transport systems with the calculated beam profiles are shown in Fig. 1. The first magnet element in this system is a pulsed switching magnet capable of switching beams of different energies and intensities to either transport system on a pulse-to-pulse basis, 360 times a second. The beam switching magnet should be able to be pulsed in either polarity in order to switch the beam left or right; the magnetic field in the magnet should be continuously variable in order to accommodate any beam energy.

The magnetic field required to switch an electron beam of $E = 25$ GeV/c through an angle $\alpha \approx \pm 0.5^\circ$ can be calculated from the equation

$$\int_0^{z_0} B(z)\, dz \approx n\, B_0\, (\ell + 2g) = \frac{\alpha\ (\text{radian})}{300}\, E\ (\text{MeV})$$

$$\approx 0.73\ \left(\frac{\text{weber}}{\text{meter}}\right)$$

where n is the number of magnets in the deflection system, ℓ is the length of each magnet, and g is the half-gap length. For the required deflection, the stored energy in the field is

$$E_m = \frac{1}{2} \int HB\, dV = 530 \text{ joules}$$

In order that the stored energy in the magnetic field might be minimized while the deflection and the length of the path are kept constant, R. F. Mozley[1] calculated the length of the deflection magnet as a function of the stored energy in the magnetic field. The minimum stored energy is that necessary to energize the pulsed magnet at its optimum length of ~60 meters. Because of this long optimum length, which would make the system very costly, a practical choice for the magnet is appreciably smaller than that given by the requirement for optimum energy storage. The magnet actually designed uses five 1-meter sections and is powered by pulsed high voltage supplies (modulators); each magnet section is excited by two modulators. The magnet can switch the beam into either of two target areas at any repetition rate up to 360 pps.

With $n = 5$, $\ell \approx 0.85$ meter, and $2g = 5$ cm, the peak magnetic field is

$$B_0 = 0.17\ (\text{weber/meter}^2)$$

Knowing the value of the required peak field in the magnet, it is worthwhile to compare the different types of magnets which can be used to realize the pulsed deflection system. Three possible alternatives, the air core magnet, the ferrite core magnet, and the laminated iron core magnet, will be considered.

Because the <u>air core magnet</u> does not have an iron circuit, the number of field lines passing through the useful volume of the gap is small, and the stray magnetic field is very extensive. In this low peak field region the air core magnet is inferior to the ferrite or iron core magnets.

The core material for the magnet may be chosen to be <u>ferrite</u>, which has a conductivity of 10^{-7} times that for metals, so that eddy current limitations are extended to much higher frequencies. A typical ferrite core magnet has a saturation flux density of 0.2-0.3 (weber/meter^2), which is larger than the required peak field. The disadvantage of this type of core material is its high

*Work supported by the U. S. Atomic Energy Commission.

(To be submitted to the 11th Annual Nuclear Science Symposium, Philadelphia, October 28-30, 1964.)

cost as compared to other core material choices.

A magnet with a laminated iron core would prevent extensive eddy current losses; in addition, its frequency response is adequate and it is economical. Laminated iron thus appeared to be the best core material for the pulsed magnet, and the magnets were designed using laminated H-type cores with multistranded water-cooled coils. Details of the design and construction of the magnet are described by H. Brechna.[2]

Optical Properties of the Pulsed Magnet System

The accuracy requirements of the magnetic field in the switching magnet can be estimated from the optical properties of the deflection system.

The optical transfer matrix for the deflection system from the exit of the pulsed magnet to the energy defining slit has the form

$$\begin{pmatrix} X \\ \theta \end{pmatrix}_{\substack{\text{quad}\\\text{input}}} = \begin{pmatrix} M_{11} & 0 \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} X_0 \\ \theta_0 \end{pmatrix}_{\substack{\text{machine + pulsed}\\\text{magnet output}}}$$

which shows that a change in the input divergence angle θ_0 into the deflection system does not change the focusing condition or the energy resolution in first-order optics. This means that the deflection system is decoupled from the pulsed magnet and the accelerator, and a change in the divergence angle due to a small amplitude variation in the magnetic field of the pulsed magnet will not influence the focusing conditions. The limit for the maximum variation in θ_0 is set by the aperture size of the input quadrupole of the deflection system. Because the half-aperture size is 4 cm and the half beam width is 2 cm, the offset distance for the beam should be less than ±2 cm. However, the change in the offset distance, b , is proportional to the change in magnetic field. The maximum for this system can be calculated from the formula

$$\delta b(\text{cm}) = 8000 \times \frac{0.5}{57} \times \frac{\Delta B}{B}$$

If $\delta b = \pm 2$ cm, then $\frac{\Delta B}{B} = 2.65 \times 10^{-2}$; using for the peak field $B = 1700$ gauss, it can be seen that the field in the pulsed magnet can change ±45 gauss. This number, however, is an order of magnitude value only, because this calculation does not take into account the finite beam divergence from the accelerator,[3] the effect of possible asymmetries in the rf circuit for the acceleration guide,[4] the possible radial electrical fields in the waveguide,[4] and the misalignment of the whole accelerator. Because of the statistical nature of these effects, an accurate calculation of the beam divergence angle caused by the variation of the field in the pulsed magnet cannot be made.[5] In order to minimize the beam divergence and the phase space introduced by the pulsed magnet system, the pulsed magnet modulators will be regulated so that

$$\sigma\left(\frac{\Delta B}{B}\right) \approx 1 \times 10^{-3}$$

or 0.1%.

General Description of the Magnet Pulser Circuit

The pulser can be described as an RLC circuit which is operated by closing a series of switches in the proper sequence (see Fig. 2). The switches are ignitrons that are turned on with trigger pulses and are turned off when the current tries to reverse direction through them.

The operation of the circuit is as follows: Capacitor C is charged to 5 kV (Figs. 2 and 3), and at time t_1 , SW1 is closed; L1 and capacitor C begin to ring with a natural frequency of 1000 cps (see Fig. 4), and the polarity across capacitor C reverses. As the voltage across capacitor C approaches -5 kV, it is monitored by a comparator which produces a trigger pulse when the capacitor voltage reaches the desired level. The trigger pulse from the comparator closes SW2. Closing SW2 places a resistor across L1 and diverts the remaining current through this resistor, thereby preventing capacitor C from charging any further. SW1 becomes reversed-biased and opens.

With the capacitor charged to an accurately known voltage, the pulser is now ready to pulse a precise amount of energy into the magnet M by closing SW3.

SW3 is closed at time t_3 (Fig. 4). The current through the magnet reaches its peak value at the time the beam passes through the magnet. At the end of one half-cycle of magnet current the capacitor is recharged to a positive voltage and SW3 opens. SW4 is now closed and the capacitor recharges to its initial value, and the cycle is complete.

Description of the Major Components

The major components of the pulser (see Fig. 3) are the ignitron switch tubes, the storage capacitor (c), the regulating circuit (L1, V2), the recharge circuit, the power supply, and the timing circuits.

Switch Tubes

The switch tubes (V1, V3) must be able to hold off 5 kV when off and carry 300 amps when triggered on. Ignitrons were chosen because they are capable of conducting long pulses of high current with low tube losses. Gridded ignitrons are required because it is necessary for the switch tube to hold off high voltage immediately after it has conducted a high current. Tests on tubes without grids showed that they did not recover their voltage hold-off capability for several milliseconds after conducting.[6]

Because SW2 and SW4 (Fig. 3) do not carry high peak currents, it is not necessary that they be gridded tubes.

Storage Capacitor

The storage capacitor consists of a 10 μF capacitor bank that is charged to both plus and minus 5 kV 360 times per second. The capacitors therefore carry current 720 times per second. The rms current rating of the capacitor must be approximately 150 amps and the voltage rating is plus and minus 5 kilovolts.

Recharge Circuit

The recharge circuit consists of a charging reactor in series with an ignitron. Because the pulser operates with a large duty cycle, the storage capacitor has to be recharged with a triggered charging tube during the interpulse period. The recharge tube conducts a small current compared to the main switch tube; therefore, a gridded tube is not required to hold off the voltage.

Timing and Trigger Circuits

The circuits used to provide the trigger pulses to the ignitrons are shown in Fig. 5. Each of these circuits consists of seven delay circuits, three triggered power supplies, four ignitor firing circuits, and two ignitron grid pulsers.

A typical delay circuit is shown in Fig. 6. The delay circuit is a standard monostable multivibrator circuit; however, care was taken to use a circuit that would recover quickly because some of the delays must operate with a large duty cycle.

The ignitor firing circuit (Fig. 7) is used to pulse the ignitors of the ignitrons. Ignitors require approximately 1/2 to 1 joule of energy per pulse to fire reliably. This energy is stored in the 8 μF capacitor (Fig. 7) by resonant charging the capacitor through L1 from the 200-volt triggered power supply. When the silicon-controlled rectifier (SCR) is triggered by the delay circuit, a negative pulse is developed at the output of this circuit. The transformer serves to invert the negative pulse as well as to isolate the SCR circuit from the floating cathode potential of the ignitron (5 kV).

The grid pulser (Fig. 8) is very similar to the ignitor pulser described above, but the grid pulser is not required to deliver much energy to the grid circuit. All that is required is a fast rising pulse of approximately 350 volts to overcome the grid bias. This pulse is usually applied 5 to 20 μsec after the ignitor pulse.

The power supply for the grid pulser and ignitor pulser (Fig. 9) is included in the timing circuits because it contains an SCR in its output which isolates the power supply from the pulser circuit until a trigger pulse is applied. By not applying a trigger to the power supply until approximately 200 microseconds before the trigger is applied to the ignitor pulser, the anode of the SCR in the ignitor pulser is at ground potential during most of the cycle, and is therefore not susceptible to noise pulses which could trigger the pulser at the wrong time.

Test Results

The power requirements of the pulser were tested by operating the pulser for 8 hours using the prototype pulsed magnet for a load. During the test the voltage across the capacitor bank (10 μF) was adjusted to approximately 5.1 kV. The energy delivered to the magnet was therefore 130 joules per pulse. The pulser was run for 8 hours at 360 pulses per second without any failures.

The efficiency of the pulser was measured by observing the voltage across the capacitor bank before and after a complete cycle of operation. Eight-five percent of the energy was recovered after each cycle while the pulser was running at full power and full repetition rate.

The accuracy of the Q-spoiling regulator circuit was tested by using a current monitor and a Tektronix Type Z preamplifier to measure the peak current in the magnet. The peak field was also measured with an E.M.R. magnetometer.[7]

Using the above testing methods, an accuracy of ±0.1% was obtained; however, the results were difficult to repeat, and further tests indicated the Q-spoiling regulator system could not be relied upon for an accuracy greater than ±0.25% with a line voltage change of ±2%.

Another method of regulation has been tested and was found to regulate to ±0.1% with a line voltage swing of ±3%. The regulator circuit is shown in Fig. 10. The circuit works as follows: SW5 is fired when the capacitor voltage is positive, causing the capacitor bank to discharge with a time constant of approximately 1 msec. When the voltage reaches a predetermined level, the comparator circuit produces a trigger which fires SW1, and the voltage across the capacitor bank reverses. Therefore, the voltage at which SW1 fires does not depend on the power supply voltage as long as the power supply voltage is greater than the voltage to which the comparator is set. The second stage of the regulator consists of a hard tube which conducts when the capacitor voltage is negative and is turned off by a comparator when the desired voltage is reached.

The first stage takes a line voltage change of ±5% and regulates to about $\pm\frac{1}{2}\%$. The second stage regulates the capacitor voltage to ±0.1%.

Field Measuring and Interlocking System

To measure the magnetic field in the pulsed magnets, the field measuring and interlocking system shown in Fig. 11 was designed.[8,9,10] An interlock gate must enable the accelerator injector, if the peak field does not vary by more than ±1%. The system must send a 50-volt pulse (from 100 ohms) to the injector, rising no later than 150 μsec before the time of the next beam pulse; the pulse width must be at least 200 μsec, with rise and fall times less than 10 μsec. The interlock setting must track the bending magnet current.

The peak value of the field must be displayed to the operator on a four-digit illuminated display with an accuracy of 0.1% of reading or ±1 digit, whichever is greater.

The system in Fig. 11 operates as follows: The trigger to the pulsed magnet that initiates the magnet current pulse triggers a 10-μsec gate generator. When the pickup coils receive a signal, the positive (or negative) level detectors put out a pulse at the time the current pulse begins. If this pulse occurs within the 10-μsec gate interval, the pulse is gated through to the 125-μsec delay generator. This generator triggers a 3.2-μsec gate generator, forming at this point a 3.2-μsec gate which is delayed 125-μsec from the beginning of the current pulse.

In the meantime, the pulsed magnet trigger has also enabled a 500-μsec gate, which gates on the integrator. The integrator output is an accurate (0.1%) replica of the magnetic field waveform. A dc reference signal (derived from the bending magnet shunts) is set to be 70.7% of the desired peak value of the field pulse, and this reference voltage, along with the integrator output, is fed into an accurate comparator whose output is a pulse when the inputs compare within 1 millivolt. The comparator pulse is ANDED with the appropriate pattern signal and presented with the 3.2-μsec gate to an AND circuit.

The AND circuit, therefore, will produce an output signal when the field reaches 70.7% of the desired value 125 ± 1.6 μsec from the beginning of the field waveform. Because the field waveform is a sine wave, it is assured that the actual peak field is equal to the desired peak field within ±1%. The output signal from the AND circuit triggers a 250-μsec pulse generator which is amplified to 50 volts and presented to the 100-ohm line through a matching transformer. Fig. 12 shows the timing involved.

Two integrators with polarity switches are used because the comparators will operate on negative levels only. Thus the polarity switches are set so that the integrator outputs are always negative.

Measurement of the magnetic field is accomplished by a sample-and-hold circuit and an A-D converter, corrected to the outputs of the integrators. A selector switch determines which of the two beams was measured; see Fig. 13 for circuit details.

Acknowledgements

The authors are most grateful to Prof. J. Ballam, Prof. R. Mozley, and Dr. R. Taylor of the Stanford Linear Accelerator Center for many helpful suggestions, and to Dr. B. Hedin of CERN for valuable discussions.

List of References

1. R. F. Mozley, Internal Report, Stanford Linear Accelerator Center, Stanford University, Stanford, California (March 1962).

2. H. Brechna, SLAC Report No. 28, Stanford Linear Accelerator Center, Stanford University, Stanford, California (May 1964).

3. C. H. Moore, S. K. Howry, and H. S. Butler, Internal Report, Stanford Linear Accelerator Center, Stanford University, Stanford, California (May 1963).

4. R. H. Helm and W.K.H. Panofsky, M-Report No. 201, Stanford Linear Accelerator Center, Stanford University, Stanford, California (November 1960).

5. H. DeStaebler, Jr., SLAC Report No. 9, Stanford Linear Accelerator Center, Stanford University, Stanford, California (November 1962).

6. J. L. Cole and J. J. Muray, SLAC Report No. 31, Stanford Linear Accelerator Center, Stanford University, Stanford, California (July 1964).

7. J. J. Muray and R. A. Scholl, SLAC Report No. 26, Stanford Linear Accelerator Center, Stanford University, Stanford, California (February 1964).

8. J. J. Muray, Internal Report, Stanford Linear Accelerator Center, Stanford University, Stanford, California (March 1963).

9. J. J. Muray and R. A. Scholl, Internal Report, Stanford Linear Accelerator Center, Stanford University, Stanford, California (August 1963).

10. R. A. Scholl, private communication.

LIST OF FIGURES

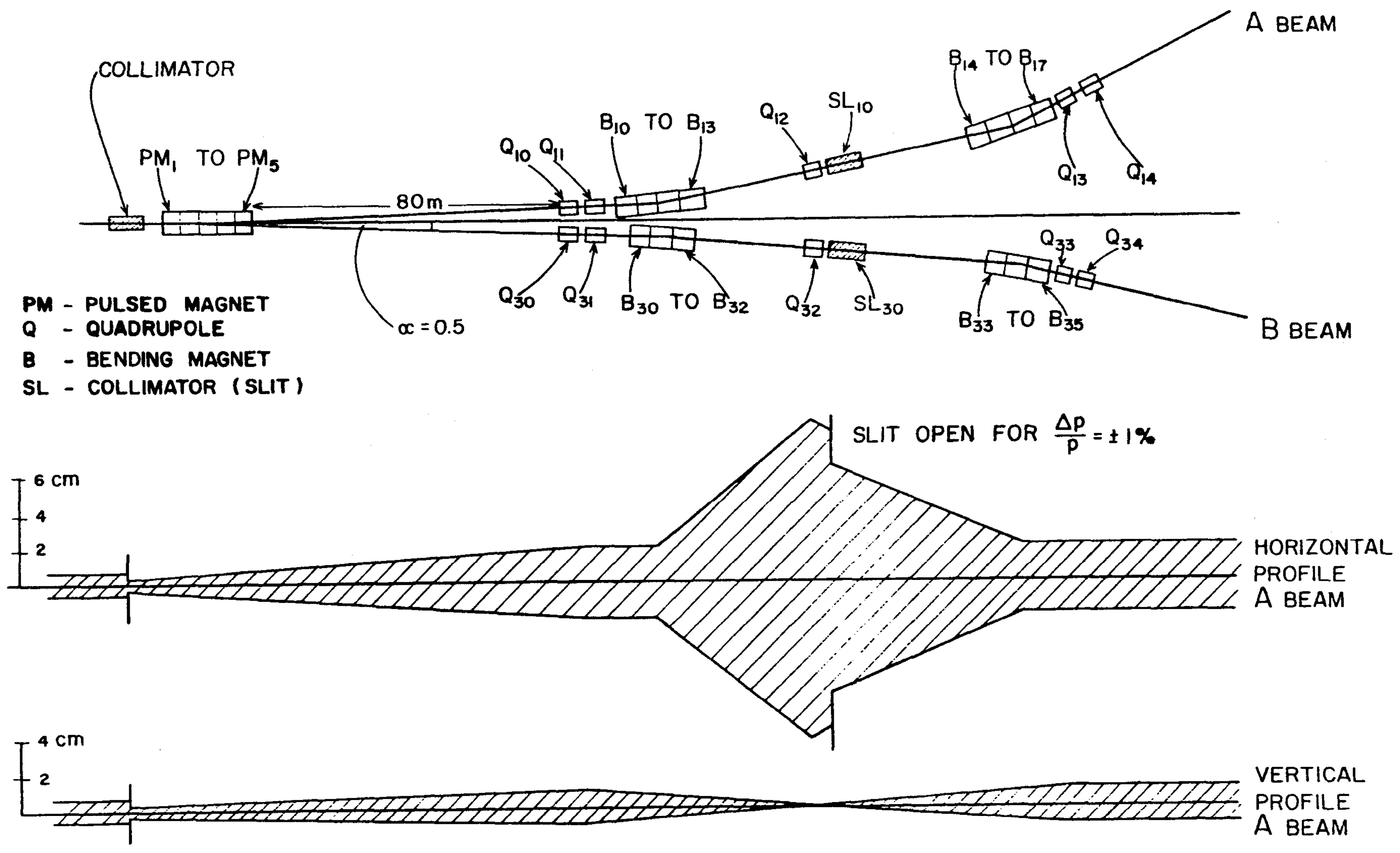
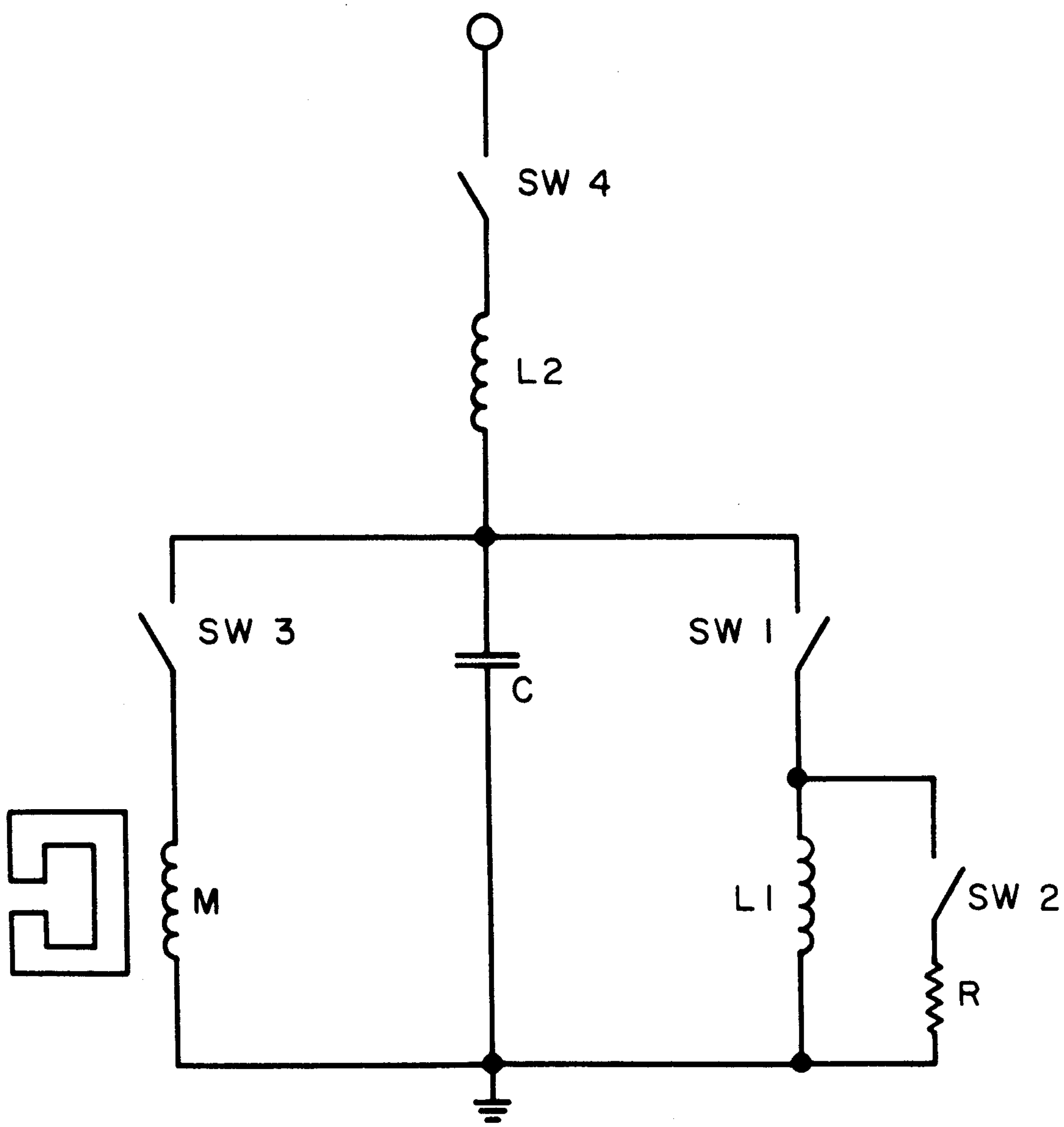


FIG. I SCHEMATIC LAYOUT OF THE BEAM SWITCHYARD AND PROFILES OF THE A BEAM



$C = 10\,\mu F$

$L_1 = 2.4\,mH$

$M = 2.4\,mH$

$L_2 \approx 1\,mH$

FIG. 2 MAGNET PULSER CIRCUIT DIAGRAM

159-2-A

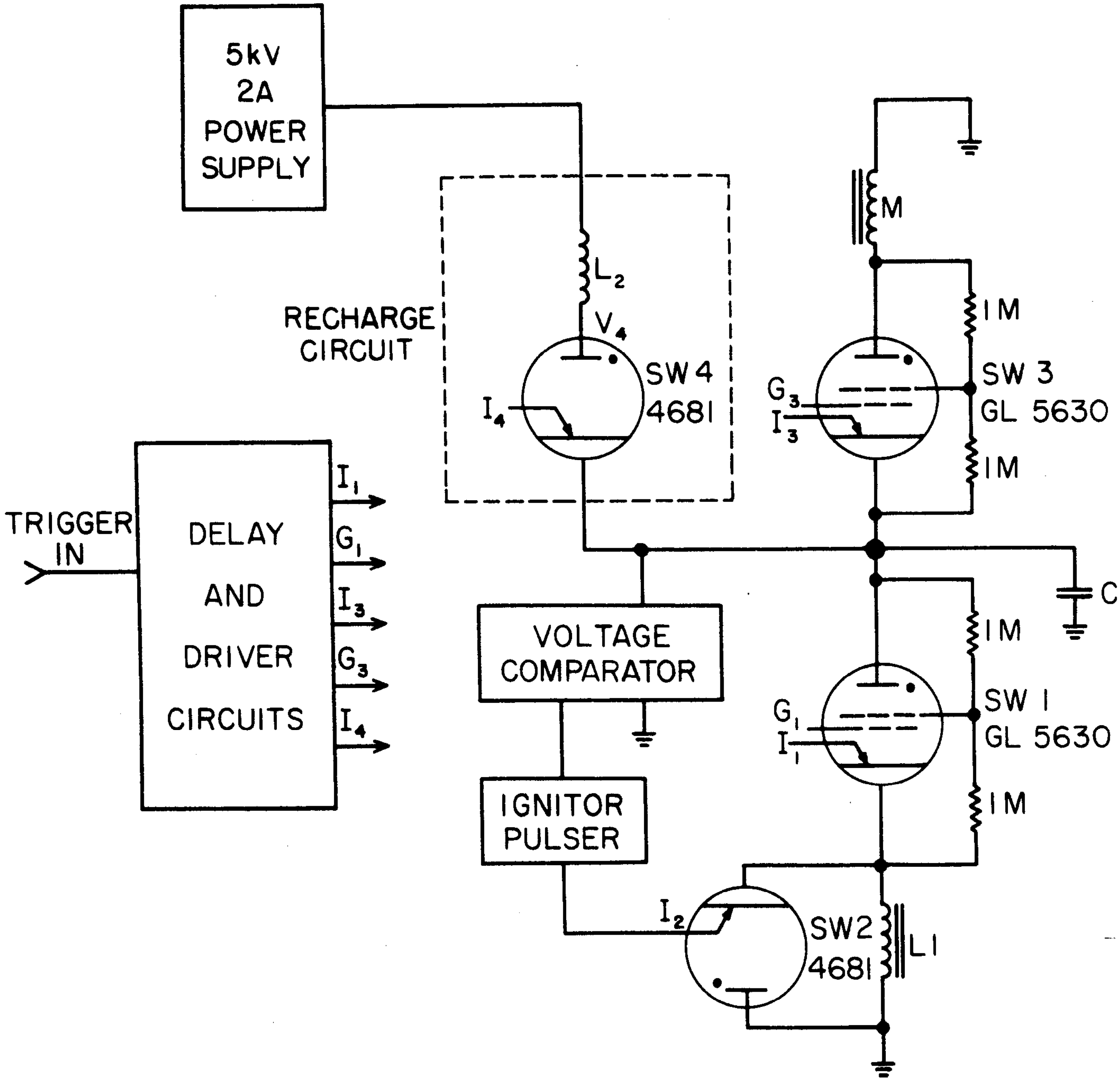


FIG. 3 MAGNET PULSER

159-3-A

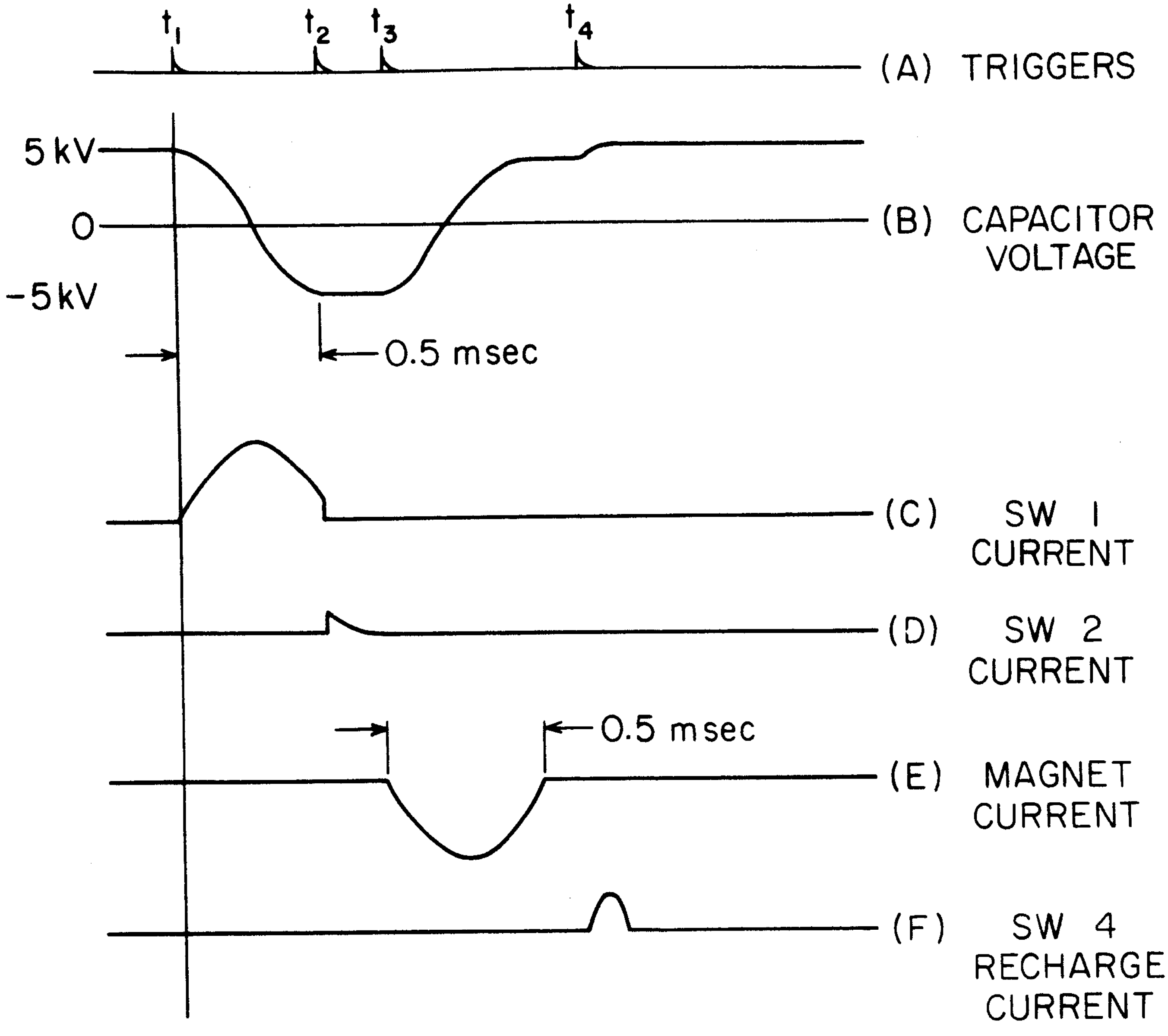


FIG. 4 WAVEFORMS

159-4-A

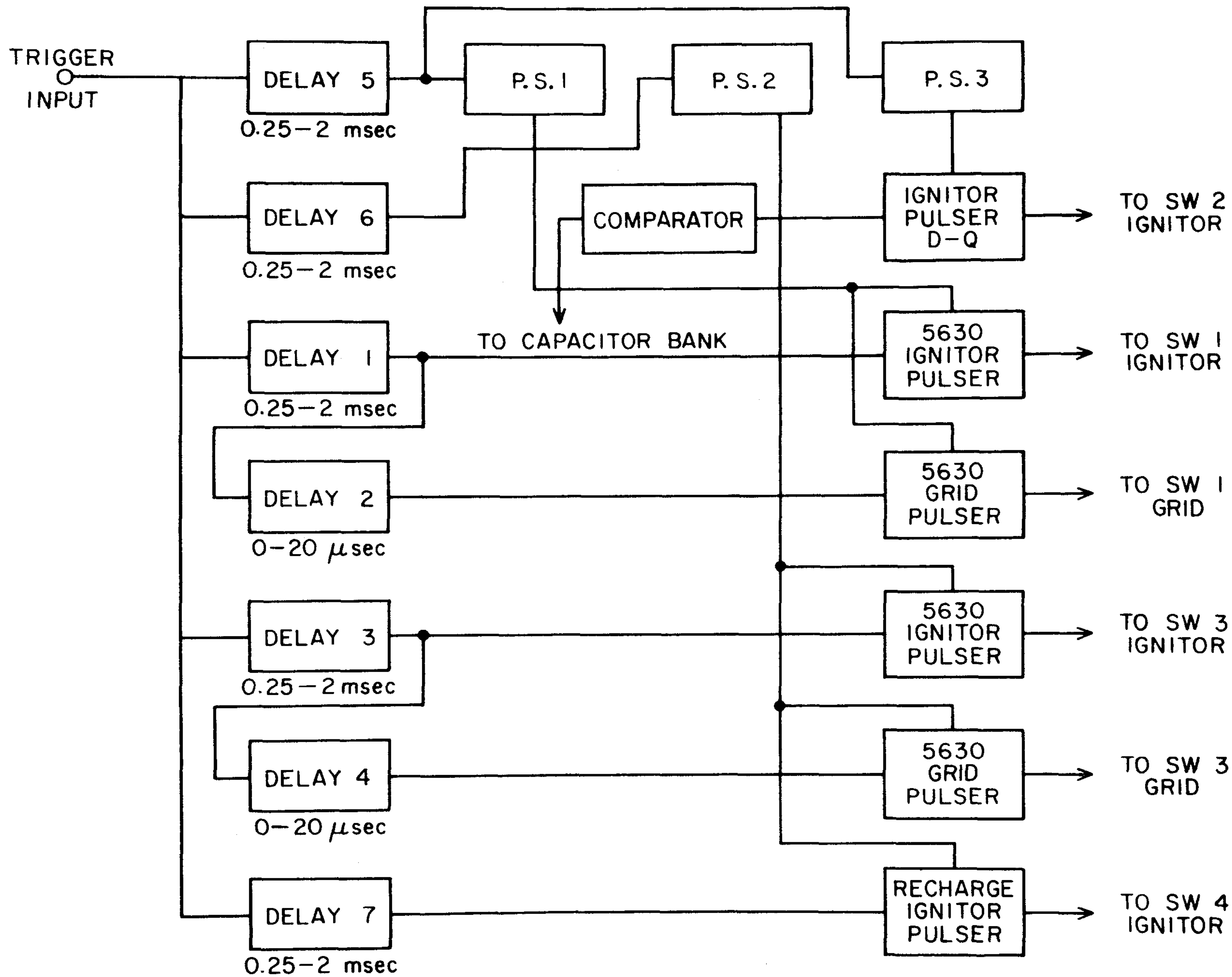


FIG. 5 TRIGGER CIRCUIT

159-5-A

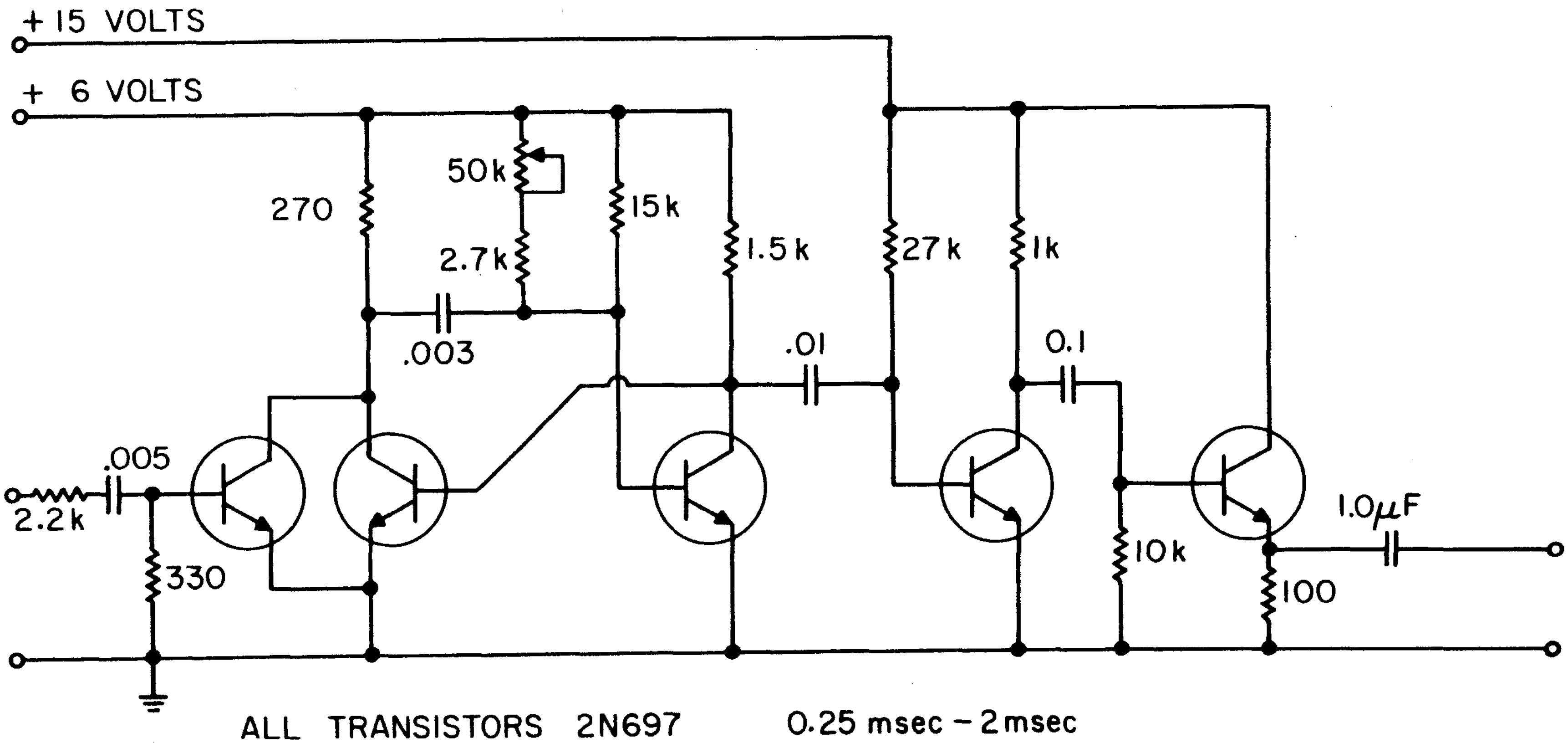


FIG. 6 DELAY CIRCUIT

159-6-A

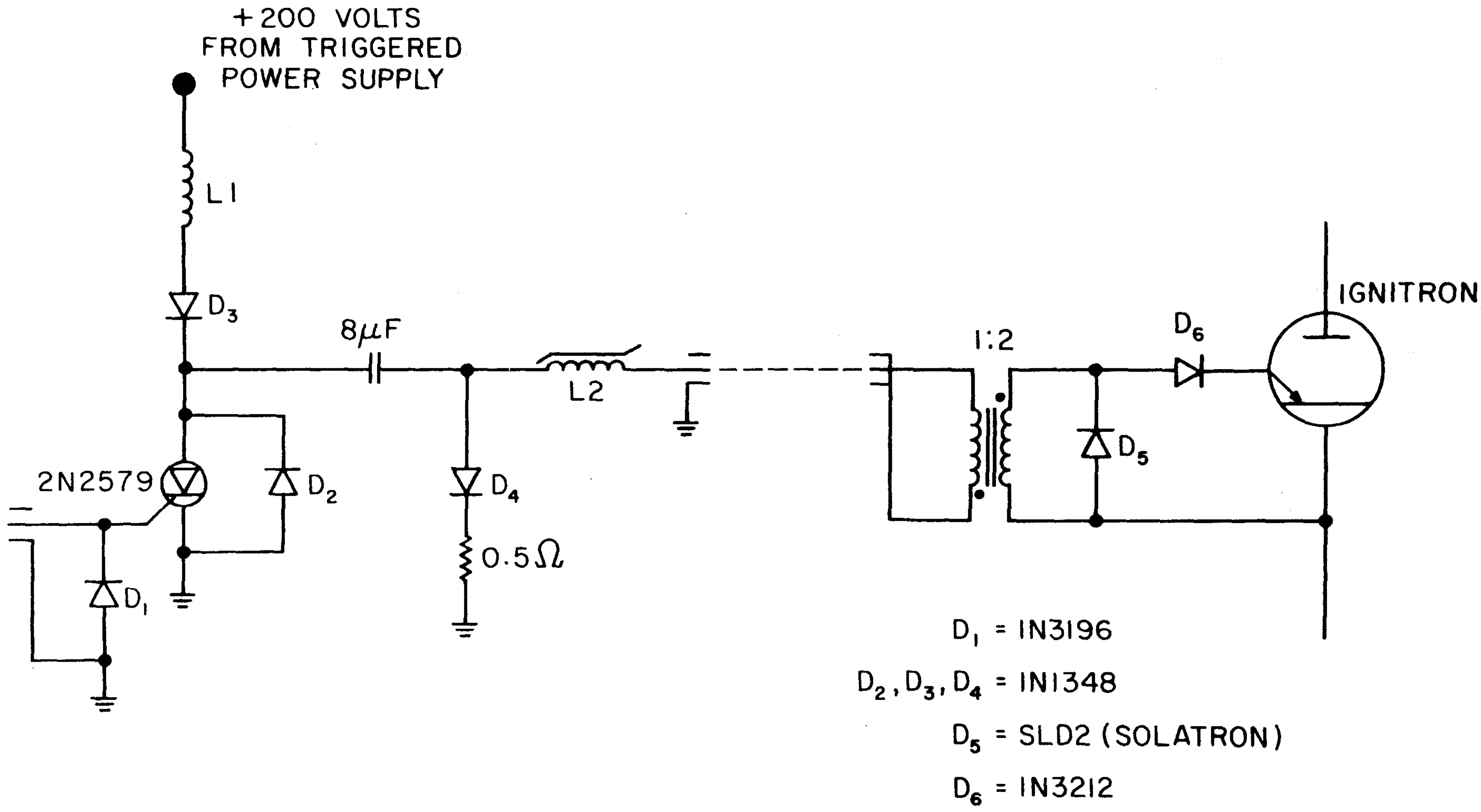


FIG. 7 IGNITOR PULSER CIRCUIT

159-7-A

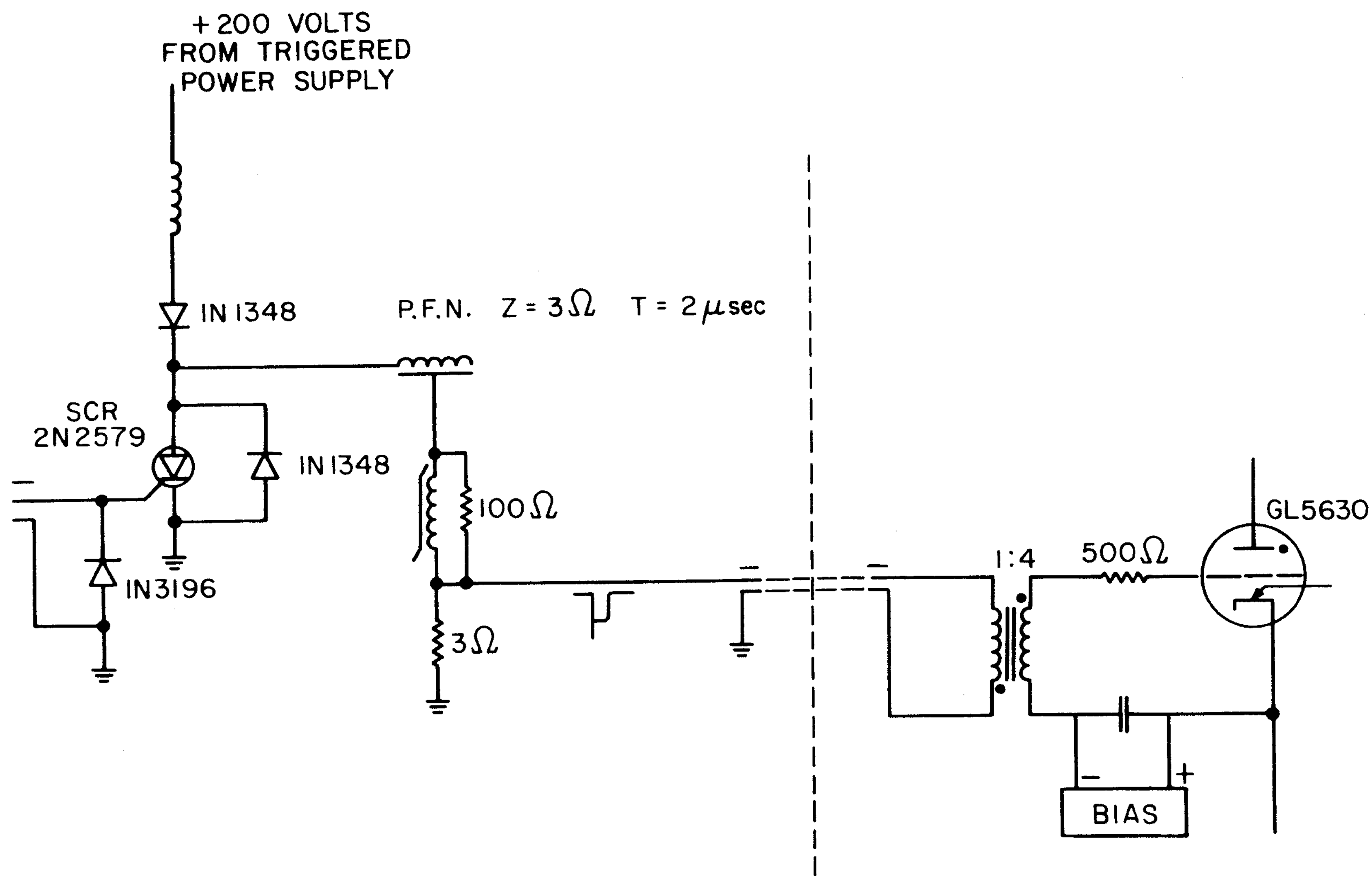


FIG. 8 IGNITRON GRID PULSER

159-8-A

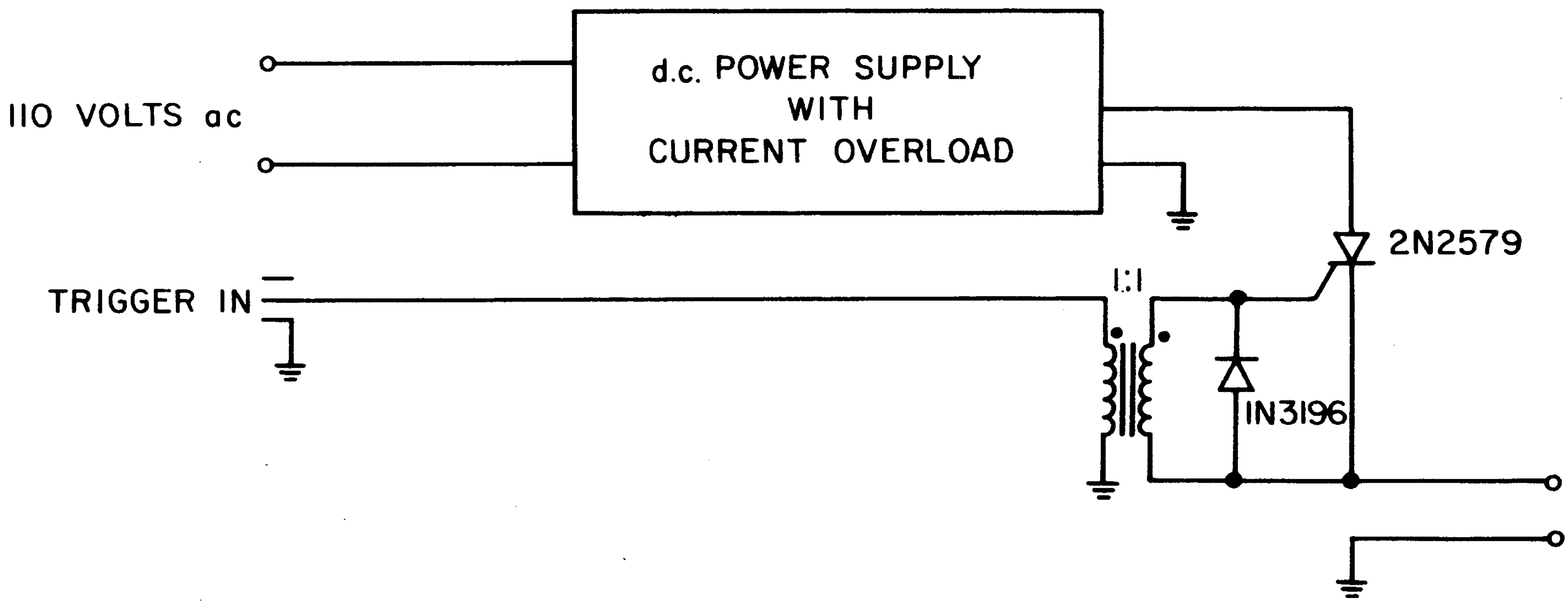


FIG. 9 POWER SUPPLY

159-9-A

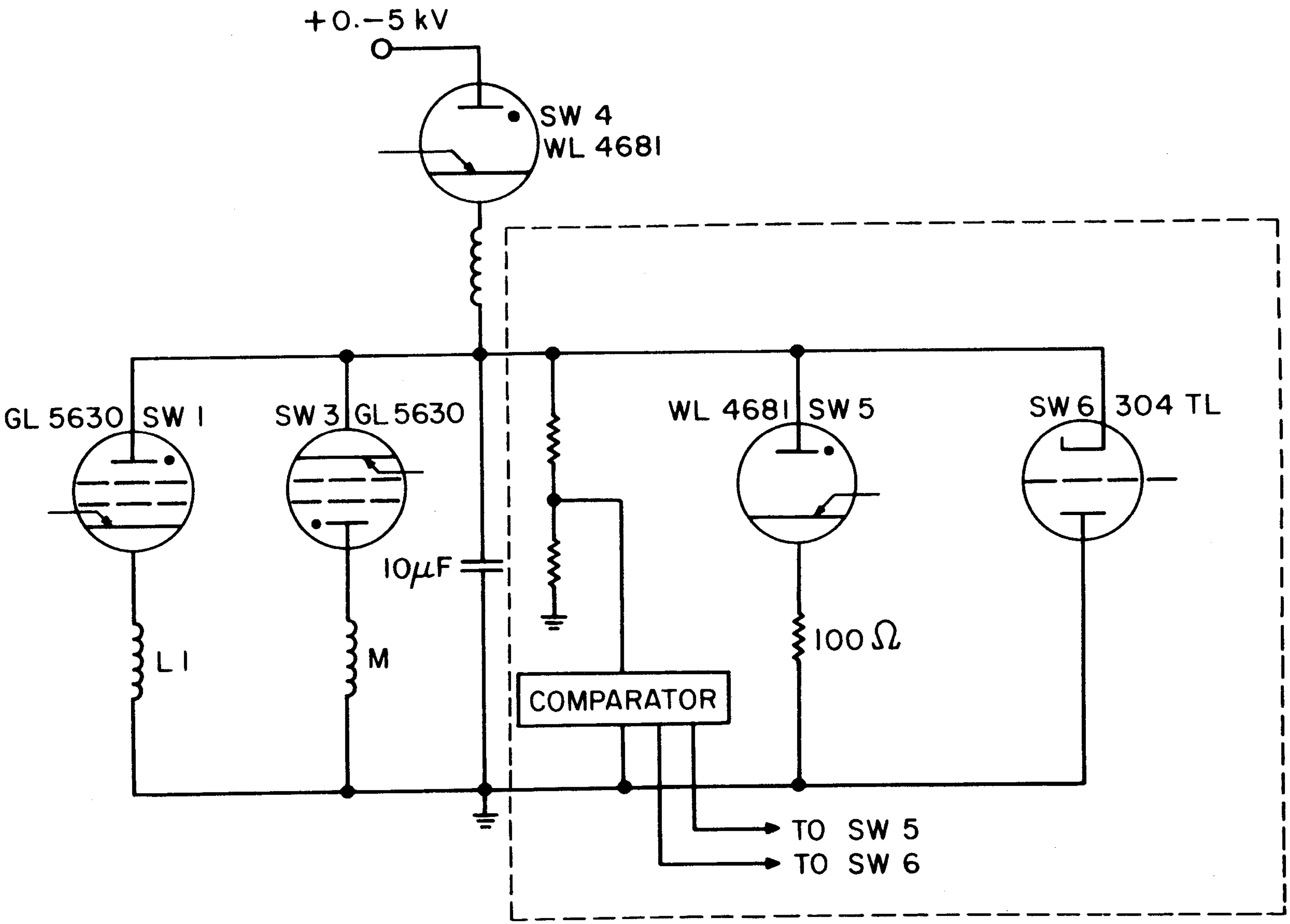


FIG. 10 TWO-STAGE REGULATOR

159-10-A

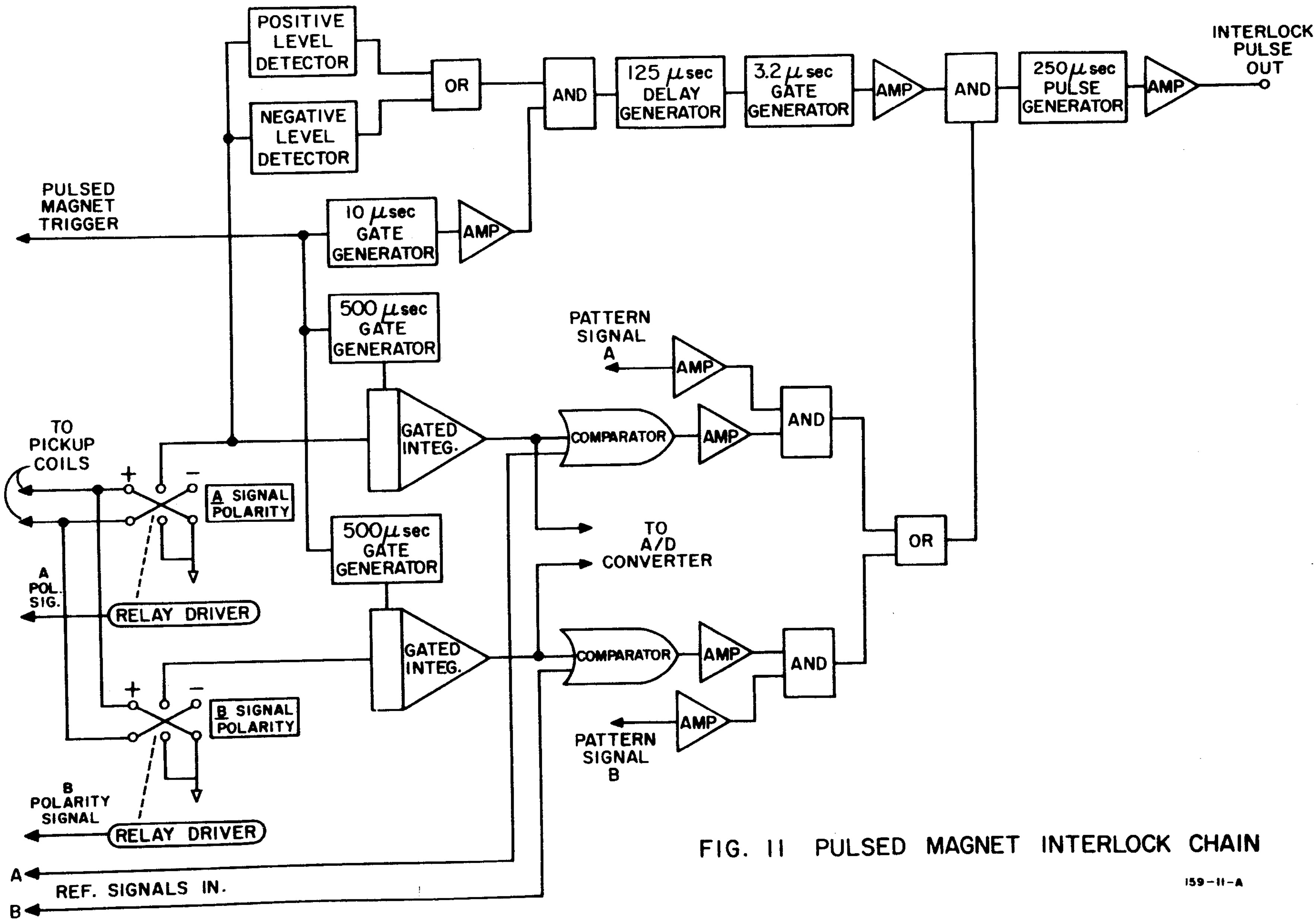


FIG. 11 PULSED MAGNET INTERLOCK CHAIN

159-11-A

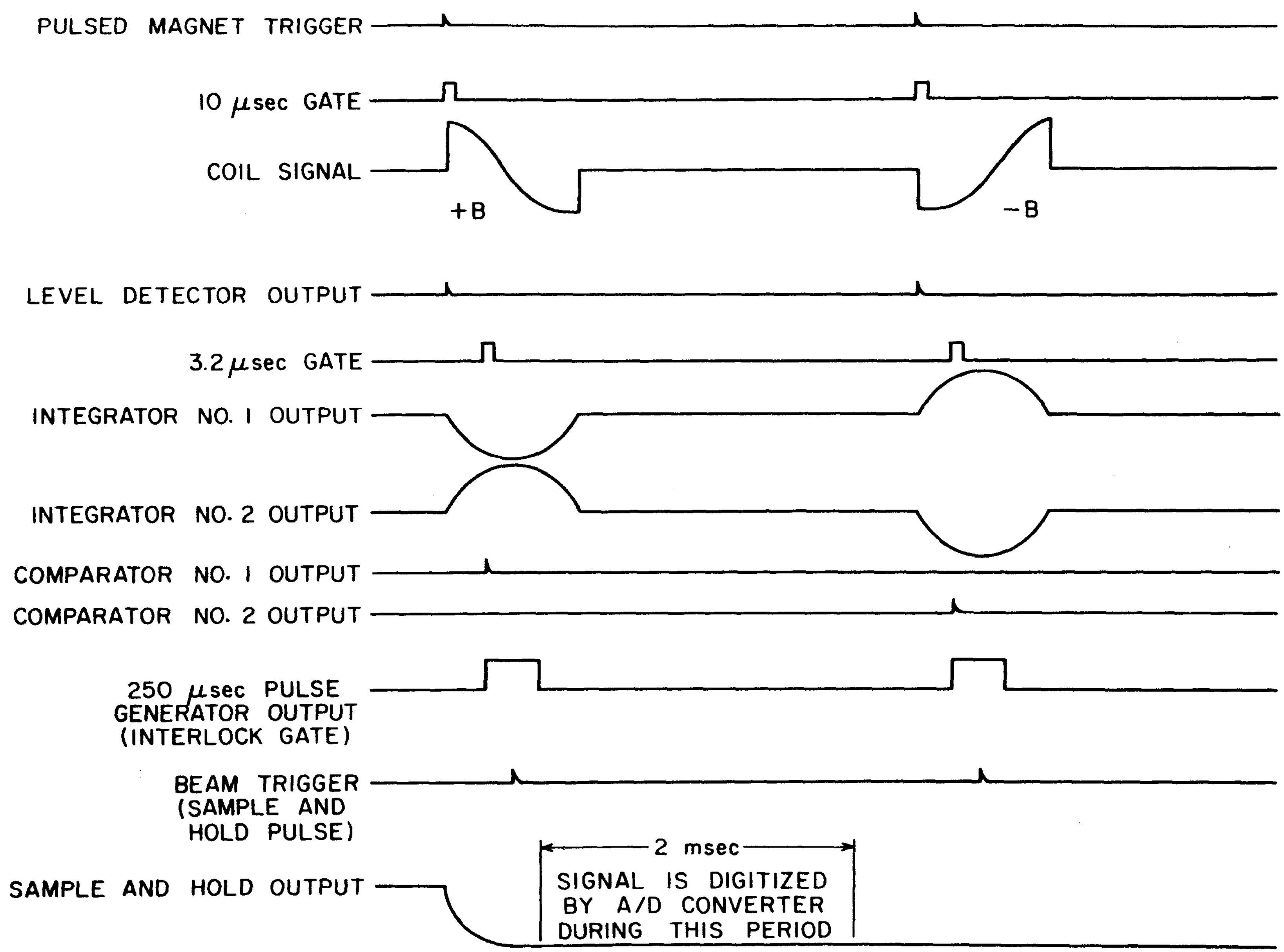
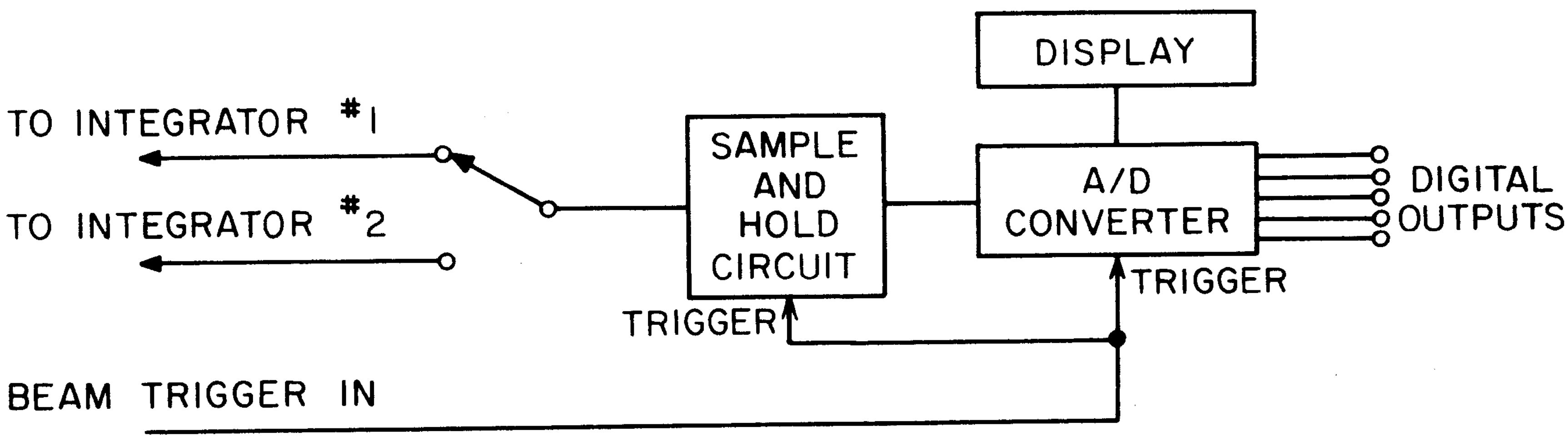


FIG. 12 INTERLOCK CIRCUIT TIMING DIAGRAM

159-12-A



159-13-A

FIG. 13 MEASUREMENT SYSTEM