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Abstract

The invention of the magnetostrictive spark chamber has created problems in detecting, digitizing, and storing the data from arrays of such chambers. These arrays are expected to vary widely in size from one experiment to another. The system of electronics developed for such use should be easily adapted to arrays of different size, and economically feasible for use with the largest arrays. Such a system is described. The basic components of the system are a preamplifier, timing discriminators, and digitizing and storage electronics. The preamplifier, designed to be mounted at the spark chamber, uses an integrated-circuit operational amplifier. It amplifies and clips the pulses from the transducer. The zero-crossing timing discriminator uses a tunnel diode in a cock-trigger circuit. The timing characteristics of the discriminator with expected variations in input pulse shape are described. The digitizing of spark location is accomplished with start/stop scalers operating with a 20-MHz clock. Scalers of 12-bit capacity can be used with chambers as large as 1 meter on a side. The digitizing and storage electronics has been designed in modular form. The number of channels (transducers) and the number of sparks per gap can be expanded or contracted as required by a given experiment. The system can be used with any of three modes of connecting the transducers: parallel, series, or parallel-series. The use of integrated circuits has led to simplifications in the design and economies in production.

1. Introduction

The data-recording system and associated electronics described here have been designed for use with magnetostrictive spark chambers of the type developed by Perez-Mendez in Refs. 1 and 2. Two criteria were followed in designing the system described. 1) It should be flexible in size and have the capacity to handle large or small arrays of chambers with various numbers of expected sparks per gap. 2) It should be relatively inexpensive so that it can be used with large arrays of chambers.

We start with a short summary of wire chambers of this type. Figure 1(a) is a schematic view of one gap of a wire spark chamber that uses magnetostrictive readout. If a spark occurs between chamber wires of the upper and lower planes, currents flow along these wires. When one of these currents passes a magnetostrictive wire, an acoustic wave is induced in the magnetostrictive wire; the wave then propagates along this wire with a characteristic velocity (typically 200 nsec per mm); when it passes an output transducer, an electric impulse is generated. The delay from the time of the spark to the impulse can be measured to determine (a) which chamber wire carried the spark current and hence, (b) one coordinate of the spark location. Note that magnetostrictive wires are close to both planes of chamber wires. Since the chamber wires in the two planes are orthogonal, two coordinates are determined for each spark in the gap.

The edges of the active area of the chamber are defined by fiducial ("start" and "stop") pulses generated automatically as shown in Fig. 1.[2] These pulses can be used to measure the propagation velocity of the magnetostrictive wire; they also eliminate the necessity of knowing accurately the position of the transducer.

2. Preamplifier

Because the typical pulses generated by transducers are about a few millivolts, they should be amplified at the chamber before being transmitted to the recording electronics. The pulses from magnetostrictive transducers contain additional lobes of opposite polarity preceding and following the main lobe; these opposite-polarity lobes are removed (e.g., by rectification) before the pulse is applied to the timing discriminator. The preamplifier described here (Fig. 2) both amplifies and rectifies. It has been developed around an integrated-circuit operational amplifier, the Fairchild μL702A. The μL702A is a differential-input amplifier, the two inputs of which are pins 2 and 3 on the diagram and the output of which is pin 7. The capacitor between pins 5 and 6 is used for frequency compensation. Power to operate the amplifier is supplied from a single power supply through the same coaxial cable that transmits the output signal. For this reason, both amplifier inputs are at +6 V dc with respect to ground.

There are two feedback loops around the amplifier. The first, active only for positive output signals, consists of CR2, R6, and R3; note that CR2 is biased to the edge of conduction by R4. The second loop–CR1, R5, and R3–becomes active when the output voltage falls below about -0.5 V. This loop helps to keep the amplifier from hard saturation during the negative lobes of the transducer signal. The diode CR2 also disconnects the output during negative excursions, and is therefore the rectifying element. The sharpness of the diode's switching characteristic

*Present address: University of California Electronics Research Laboratory is enhanced by its being placed in the feedback loop. The amplifier is capable of producing an output pulse of 1.5 volts amplitude into a 50-ohm load. The input-output transfer characteristic of a typical amplifier intercepts the output voltage axis at -20 mV, the voltage required to fully turn on CR2.

As shown in Fig. 3, the preamplifier is built into a metal case along with the transducer and its magnetic shield. The three set screws at the top apply pressure to a rubber tubing which damps the magnetostrictive wire and prevents acoustic reflections from impinging on the transducer.

3. Timing Discriminator

The timing discriminator accurately marks the arrival time of the "meaningful" portion of each rectified and amplified pulse from the transducer, in spite of certain departures from the ideal of the shapes and amplitudes of the pulses. There are three characteristics of a pulse which affect the operation of the timing discriminator: (a) spark chambers have a tendency to produce currents in more than one wire of the chamber; (b) the amplitudes of the pulses vary according to the number of sparks per event in the gap; (c) pairs of pulses may result from sparks separated by as little as 2 mm.*

We have found that a zero-crossing discriminator preceded by a differentiating network with a time constant of 40 to 80 nsec works well. The circuit of such a discriminator is shown in Fig. 4, and waveforms pertinent to the operation of the discriminator are in Fig. 5. A tunnel diode, used in a familiar mode in which the input signal must rise to a certain level before the circuit is "cocked," helps to discriminate against noise; it then "triggers" at the true zero-crossing point of the differentiated waveform. Since the load line of the tunnel diode is essentially horizontal, it will trigger at the true zero crossing if the quiescent point (Q in Fig. 6) is set at a current equal to the peak current of the diode. The quiescent or bias current is set by R2 of Fig. 5. Pushing the "set-bias" pushbutton PB1 puts the diode into its low-current state after which R2 is adjusted until the diode just trips to its high-current state. The bias is then set.

Clearly the output pulse of such a discriminator will be independent of amplitude as long as the shape of the input pulse is constant. As noted above, variations in the shape of the pulse can occur when sparks produce currents on adjacent wires of the chamber. The effect of such variations has been investigated in the way depicted in Fig. 6. Currents from a pulse generator flowed on two wires 1 mm apart; rectangular pulses 40-nsec wide were used. The sum of the currents was held constant at 40 A. This current amplitude is less than the saturation level of the magnetostrictive element. The ratio of the two currents was varied and the changes in timing of the discriminator-output pulse were noted. The results, shown in Fig. 7(b), suggest the possibility of measuring the position of a spark to a resolution greater than the wire spacing. In particular, if the currents in the two wires of the chamber are the same, the discriminator measures the spark location as centered between the two wires (i.e., 100 nsec later than if all the current flows in the wire nearer to the transducer).

One test was made with currents flowing in three adjacent wires, again spaced 1 mm apart. Fifty percent of the total current flowed in the center wire, and 25% in each of the two outer wires. The output of the discriminator occurred at the same time (± 10 nsec) as if all the current flowed in the center wire.

The two-spark resolution was examined by passing currents through two wires spaced 2, 3, and 4 mm apart, with results shown in Fig. 7. Linear operation is again assumed--i.e., the currents are below the value that saturates the magnetostrictive line. The peak of the curve at the 3-mm spacing can be explained with the aid of Fig. 8, in which the peak of the transducer-output waveform, B, which would result from current in the nearer wire, falls directly over a rising part of the waveform A, associated with the farther wire. When these two waveforms are linearly added, the peak of the resultant is shifted from the peak of waveform B. The shift increases as the amplitude of the later waveform decreases, and the positional error amounts to 1/4 mm when the amplitude of waveform B is one-half that of A.

4. Arrays of Magnetostrictive Lines

There are at least three modes of transporting the transducer outputs to the digitizing and storage device: parallel, series, and parallel-series. In the parallel mode, depicted in Fig. 9, the outputs of all N transducers are brought to the storage unit without delay. Immediately following the pulsing of the chamber, all lines carry information to the storage device; in the extreme case, pulses from the transducers may arrive at the storage unit and require processing simultaneously, thus a storage unit capable of servicing all N inputs simultaneously is required. In the scheme of electronics described herein, this requirement necessitates N timing discriminators and N × M words of temporary storage, where M is the maximum number of sparks per transducer that the recorder is designed to handle. Following an event, the dead time of the system is (a) the propagation time down the longest magnetostrictive line plus (b) the time to transfer the N × M words of temporary storage to the data recorder. In a modest array of spark chambers 1 meter on

*In our case the chamber-wire pitch is 1 mm, and the resolving power of the magnetostrictive line is such that pulses due to sparks 1 mm apart are not separated. This is no limitation, since currents in adjacent wires are probably due to a single spark.

a side, it is practical to think of dead times of 1 msec or less.

In the series mode the active periods of the individual transducers are queued, with one magnetostrictive line completely read out before the contents of the next are delivered, and so on. The queuing can be accomplished, for example, by connecting all the magnetostrictive lines in series, or more practically, by feeding them into a tapped delay line. This mode requires only one discriminator and M words of temporary storage. Additional rough timing is required to find the "start" pulse of each line as it arrives. The dead time is (a) the sum of the time needed to transfer $N \times M$ words to the data recorder plus (b) the sum of the propagation times of the N magnetostrictive lines. Since the propagation velocity on the lines is 200 μsec per meter, the dead time is probably much greater than 1 msec.

The parallel-series system consists of several parallel circuits, each consisting of several lines in series. It effects a compromise between lots of electronics and long dead time.

5. Methods of Digitization and Storage

The 200-nsec-per-mm propagation delay of the magnetostrictive line makes it practical to use a gated clock and scaler system for measuring the spark positions. A 20-MHz clock, for example, provides a least count of 1/4 mm. Similar systems are commonly used in the sonic spark-chamber field, where, however, the propagation velocities are an order of magnitude slower.[4]

We have developed a system of start-stop scalers using integrated circuits as the scaling and logic elements. A block diagram showing the organization is in Fig. 10. Each transducer channel has one discriminator, M scalers, and a distributor, the last of which controls the gating of the scalers in synchronism with the arriving pulses from the transducer.

Figure 11 is a simplified block diagram of a distributor and portions of the four scalers attached to it. Four scalers can digitize the positions of as many as four sparks. The number of scalers can be changed at will; the printed circuit card for the distributor has space for controlling eight. All the flip-flops are RTL integrated-circuit J-K flip-flops (Fairchild μL926). Those labeled SR1 through SR4 are connected as a shift register; they control the sequencing of the scalers during both the read-in and read-out phases.

The read-in process will be described first with the aid of the waveform on Fig. 12. At time t_0, the instant the spark chamber is triggered, a reset pulse several microseconds long is applied; it forcibly holds all flip-flops in the reset state until the noise from the chamber firing has died. At time t_1 the start fiducial pulse arrives and causes SR0 to be set; this in turn sets SR1 through SR4. As a result the gate inputs of the scaler input flip-flops, $SC1_0$ through $SC4_0$, are all put into the low state, allowing them to start accepting and counting the clock pulses. At time t_2, the arrival of a pulse due to a spark causes flip-flop SR1 to be reset, which stops the scaling process in scaler 1. At t_3 the arrival of a pulse due to a second spark terminates the scaling in scaler two. In the example, there are only two sparks in the gap. The stop fiducial pulse at t_4 stops scaler three, but scaler four continues counting until the clock is stopped externally at t_5.

Thus, if there are three or fewer sparks, a number corresponding to the delay between the start and stop fiducials is contained in one of the scalers. The computer that analyzes the data can be programmed to recognize this characteristic number, and use it to calibrate the results against any drifts in the propagation velocity of the magnetostrictive line. If four sparks occur in a particular event, the fiducial distance is not digitized, and the computer must assume that the propagation velocity has not drifted.

Each scaler consists of 12 flip-flops connected as a 12-bit ripple-carry binary scaler. With a 20-Mc clock, the length of magnetostrictive line corresponding to 4095 counts (the capacity of a 12-bit scaler) is slightly more than 1 meter. Although additional bits can be added for larger chambers, 12 bits is a convenient word size for many computers.

The shift register SR1-4 is also used to commutate the outputs of the scalers into the permanent storage device during the readout cycle; part of the circuits necessary to accomplish this is shown in Fig. 12. At the start of readout, the in/out control signal is set to zero. Then when the first readout advance command occurs, only the first flip-flop, SR1, is set to 1; the others remain in their 0 condition. Additional advance commands cause the single "1" to be advanced to SR2, then SR3, etc. This sequence causes the individual scalers to be connected in turn to the 12 output wires. During readout, the shift registers from each transducer channel are connected in series (by means not shown in Fig. 12). Thus, after the last scaler of channel one is read out, the first scaler of channel two is read out, etc.

Figure 12 is a photograph of a printed circuit card containing a discriminator and a distributor. Although the card has places for eight flip-flops in the shift register, only four of them are wired in.

Figure 13 is a photograph of a partially filled card drawer containing four distributors, four discriminators, and sixteen scalers (N = 4, M = 4). The drawer is a complete self-contained unit, capable of accepting the outputs of four transducer preamplifiers, digitizing and temporarily storing the data. It can communicate its own data and that of other similar drawers directly to a computer or other permanent-storage device in a conversational (request 12-bit word/accept

12-bit word) mode. The system can be expanded or contracted to accomodate various values of N and M as required by a given experiment.

The use of integrated circuits has resulted in a compact system that is much less expensive than, for example, systems constructed with the scalers normally used in physics experiments. The cost of constructing the 12-bit scalers with readout gates (including drawer hardware, but less power supplies) is approximately $150. The cost of the distributor card is about $200.

A second storage system utilizing a thin-film memory as the storage element is under development. The prototype system will have a storage capacity of 128 words. Digitization is accomplished by transferring the contents of the single scaler to the appropriate word location(s) of the thin-film memory at the instant that a pulse arrives from one or more transducers. We developed a 12-bit scaler with a settling time of less than 20 nsec for this purpose. A look-ahead carry scheme is used to achieve this fast response. If a 20-MHz clock is used, a period of 30 nsec obtains during each cycle when the contents of the scaler are stable and may be transferred to the thin-film memory.

We expect that the thin-film memory system will be more economical than the integrated-circuit scaler system when more than about twenty 12-bit words per event are stored.

Acknowledgments

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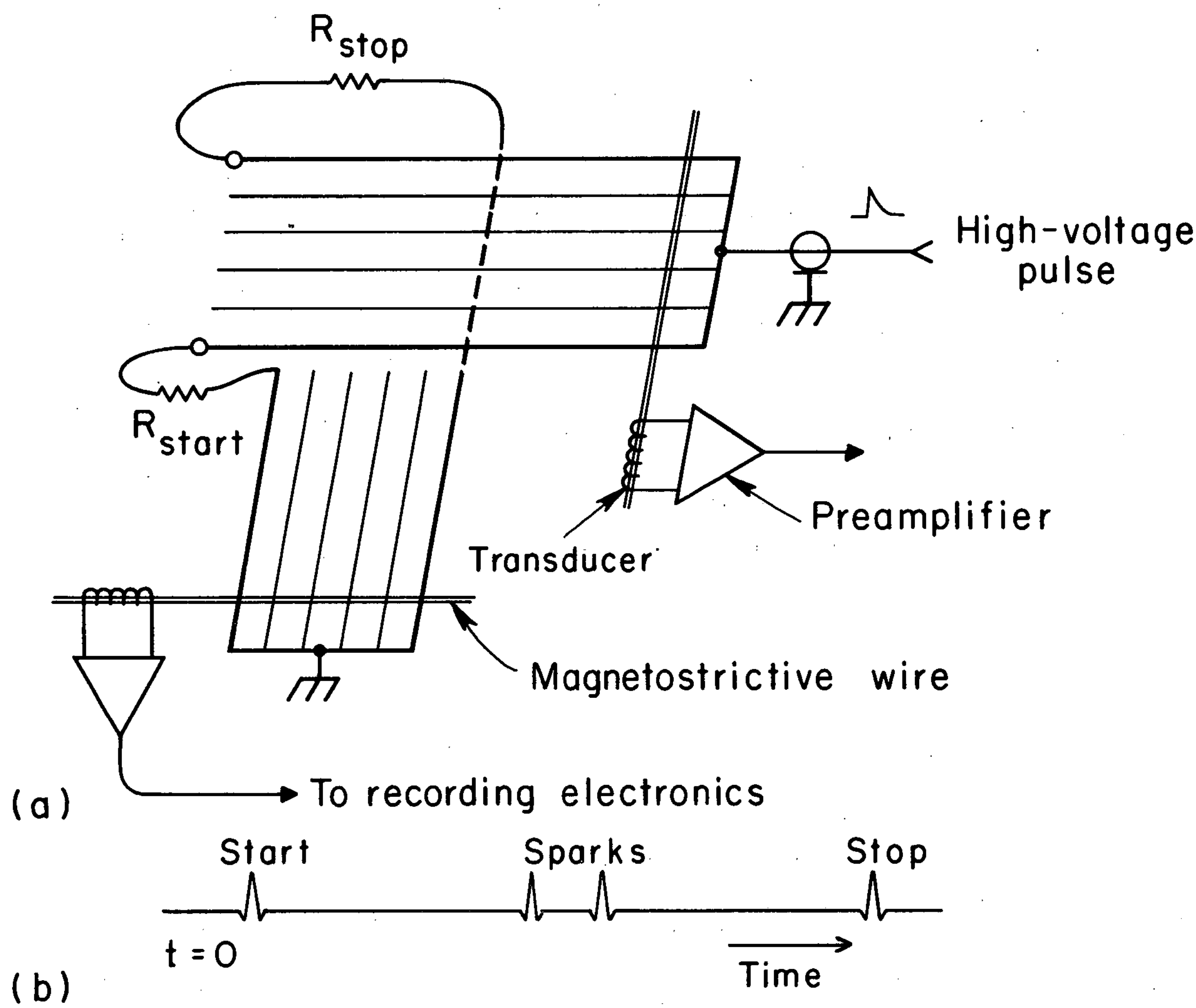
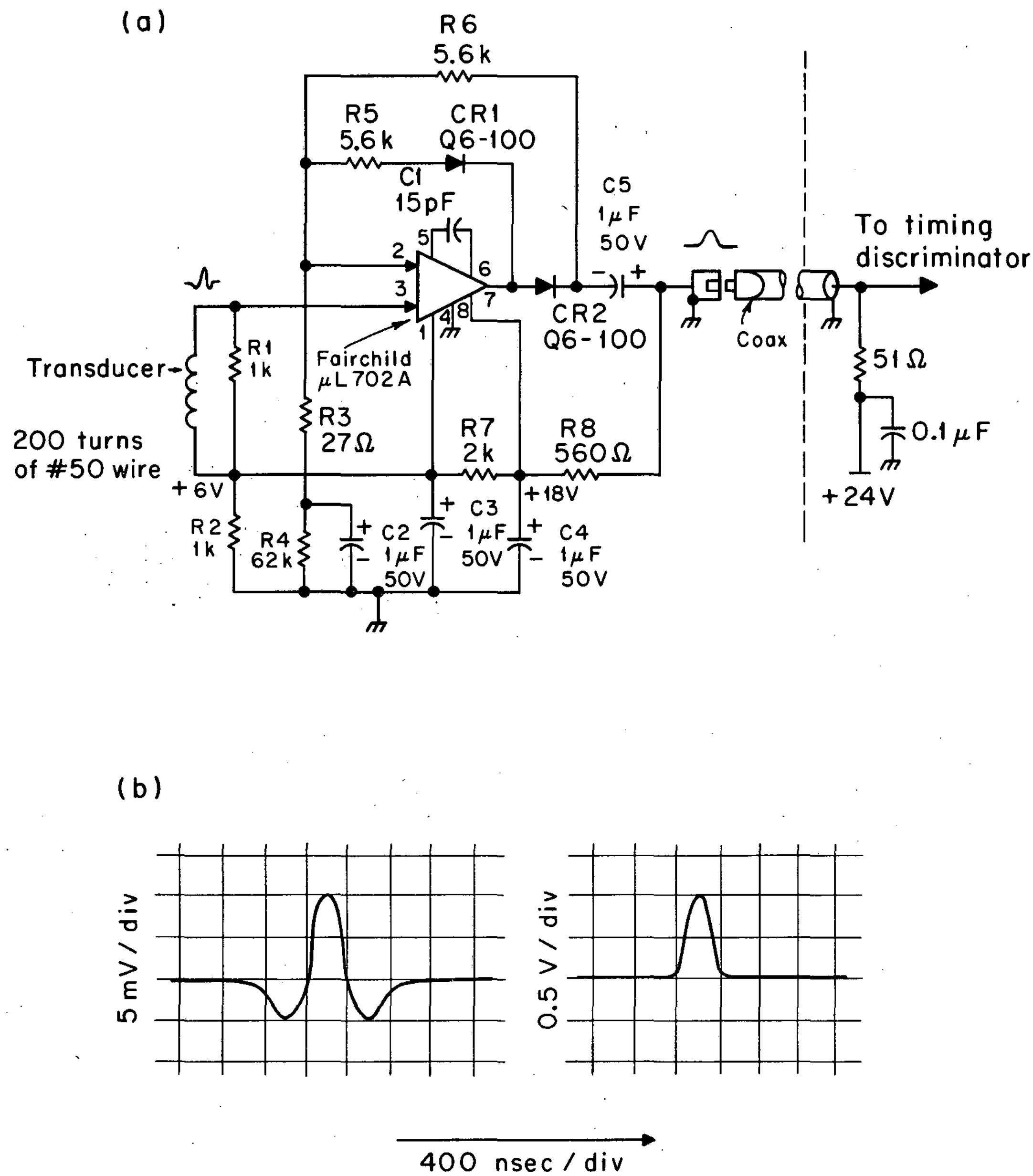


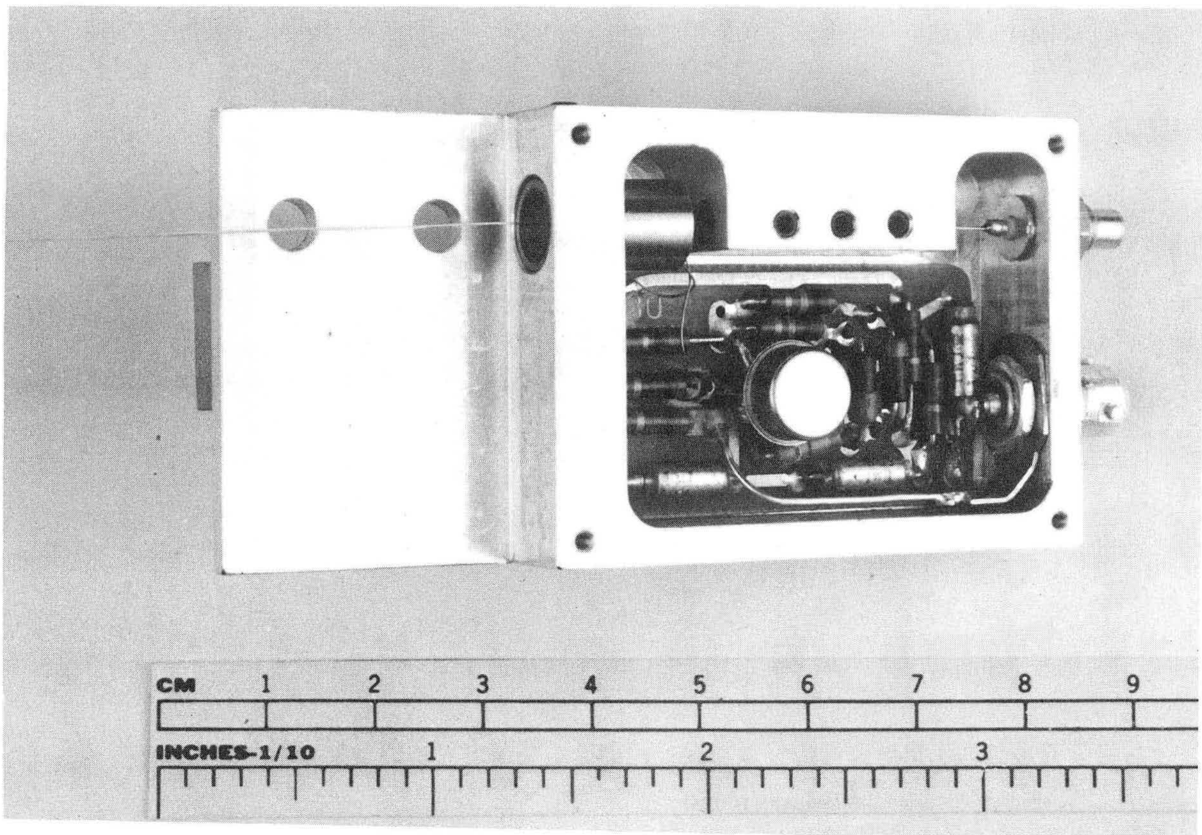
MUB-9800

Fig. 1. (a) Schematic of a single gap of a wire spark chamber with magnetostrictive readouts on both planes of wires. The method of generating start and stop fiducials is shown. (b) Typical output waveform of a transducer.



MUB-9801

Fig. 2. (a) Preamplifier circuit diagram. The Fairchild μL702A is an integrated-circuit operational amplifier. The preamplifier has a voltage gain of 200.
(b) Typical input (left) and output (right) waveforms.



ZN-5399

Fig. 3. Mounted preamplifier. At the upper left the magnetostrictive wire enters the transducer which is inside the cylindrical magnetic shield.

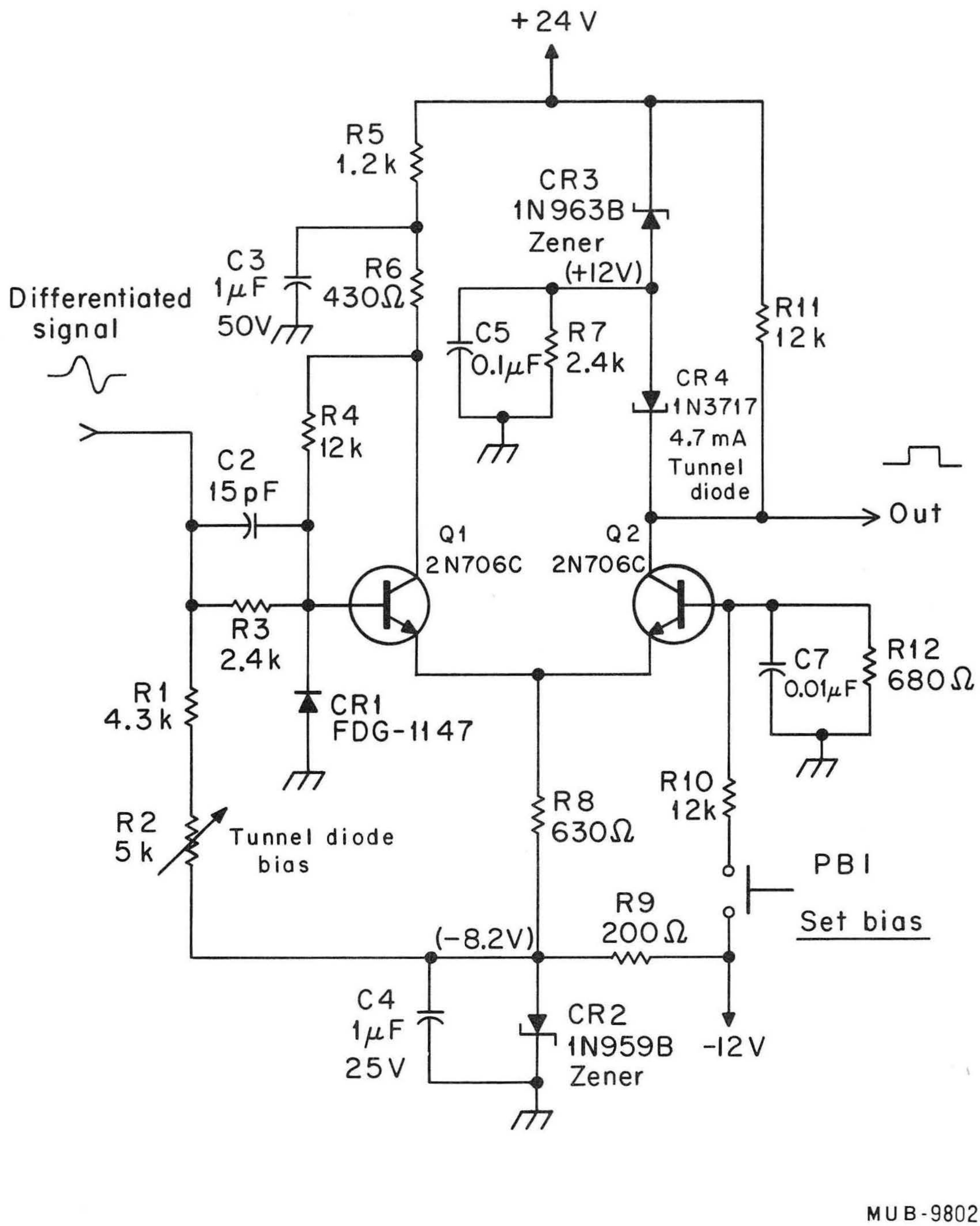


Fig. 4. Circuit diagram of the zero-crossing discriminator. The signal from a preamplifier is passed through an 80-nsec differentiating network before being applied to this circuit.

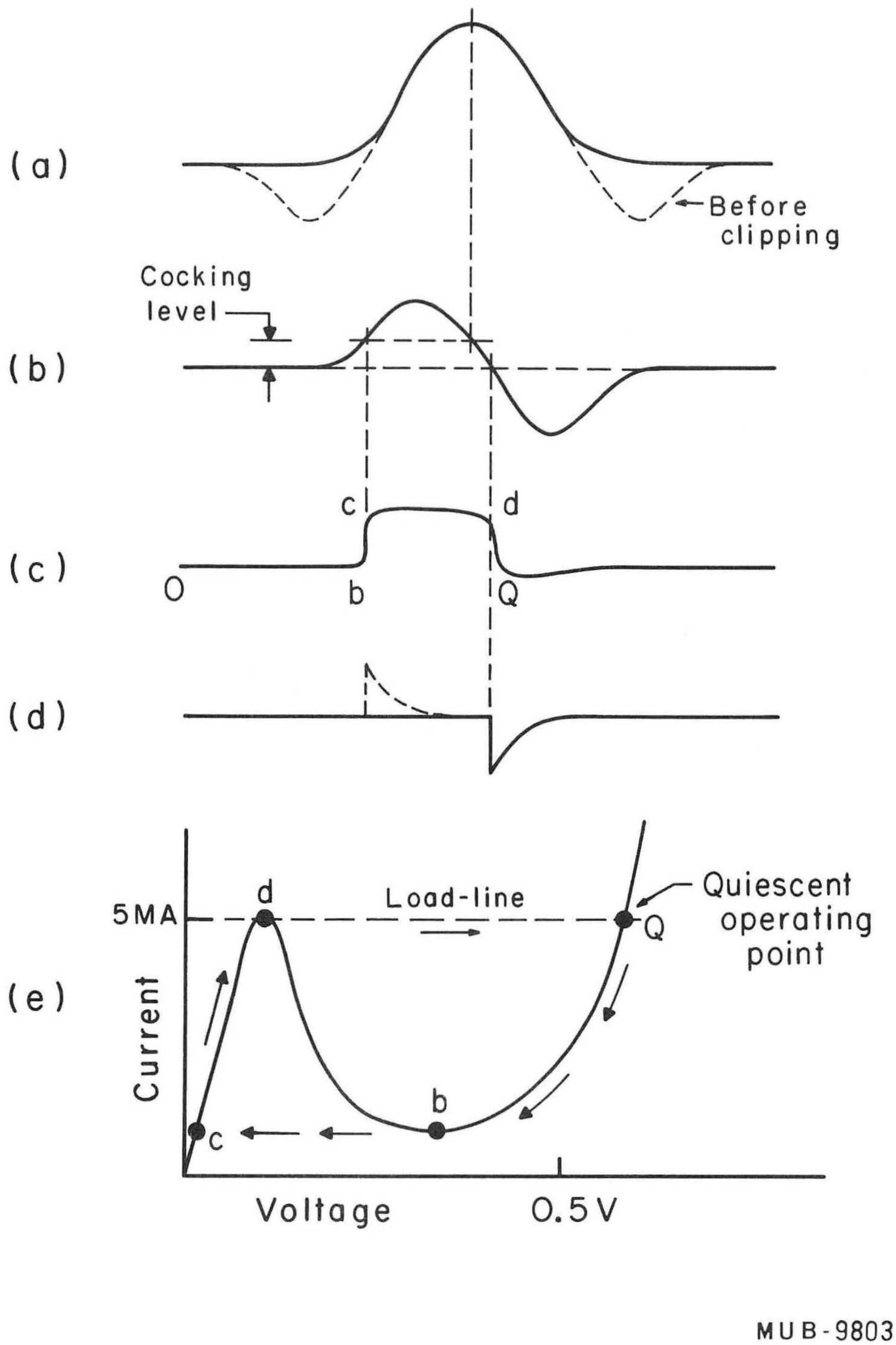


Fig. 5. Waveforms associated with the zero-crossing discriminator of Fig. 4.
(a) Signal from the preamplifier.
(b) Same as (a) after passing through the differentiating network.
(c) Voltage across the tunnel diode.
(d) Same as (c) after differentiation and clipping.
(e) Operating points on tunnel-diode characteristic.

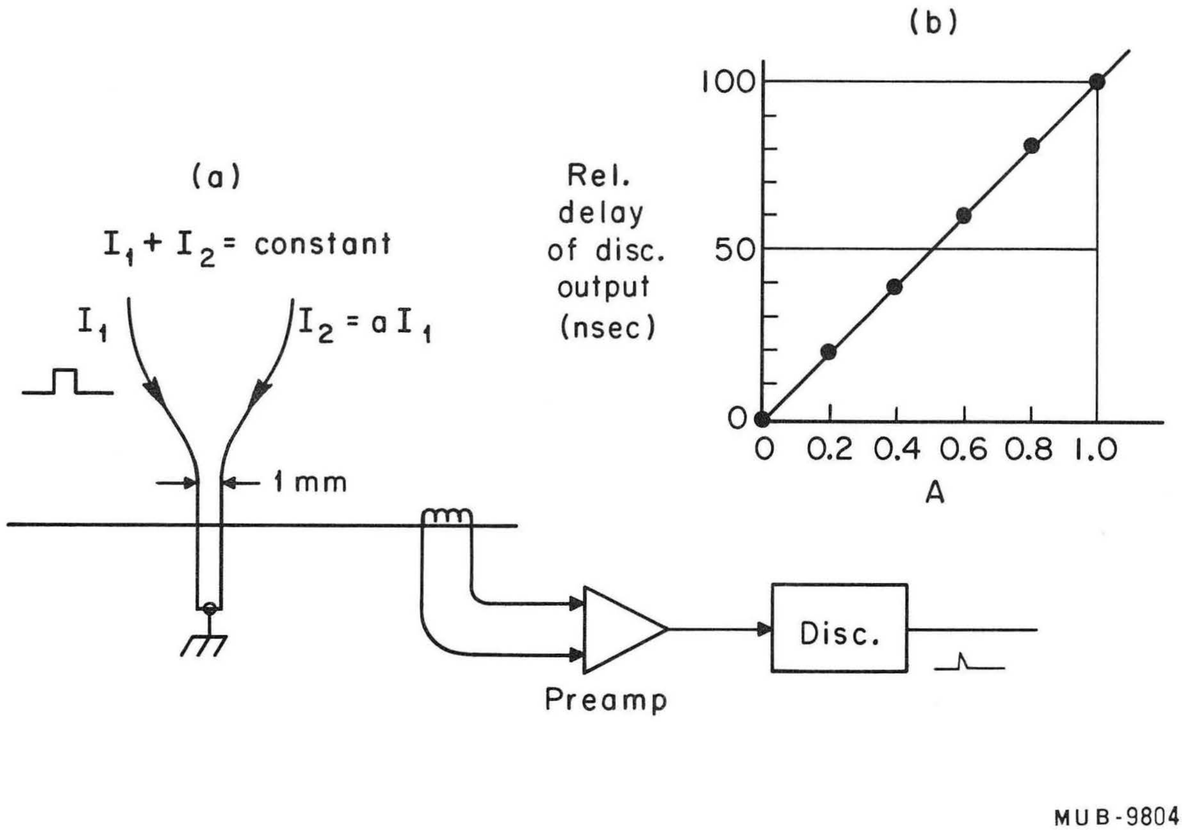
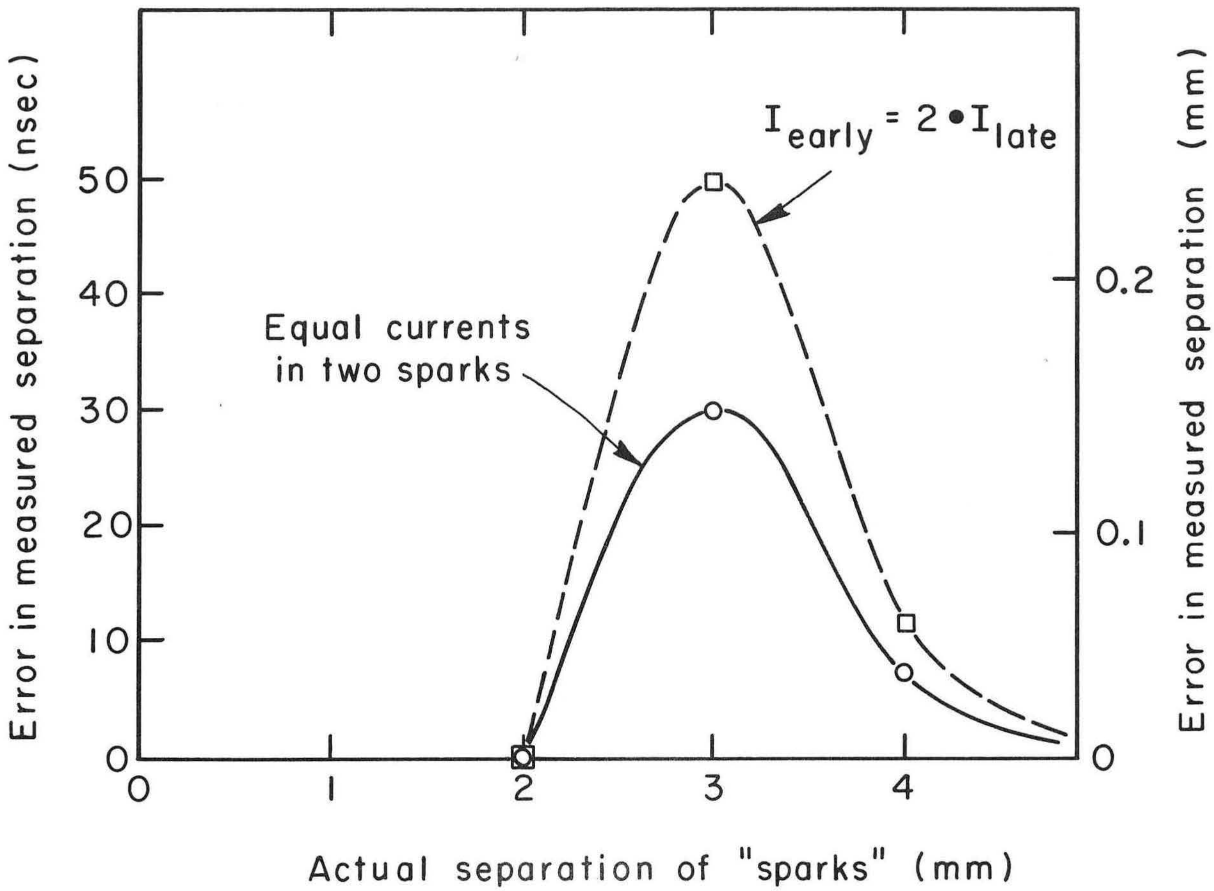


Fig. 6. Measurements on simulated sparks inducing currents in two adjacent wires of a spark chamber.
(a) Schematic of measuring scheme.
(b) Results.



MUB-9805

Fig. 7. Results of measurements on two-spark resolution made with simulated sparks.

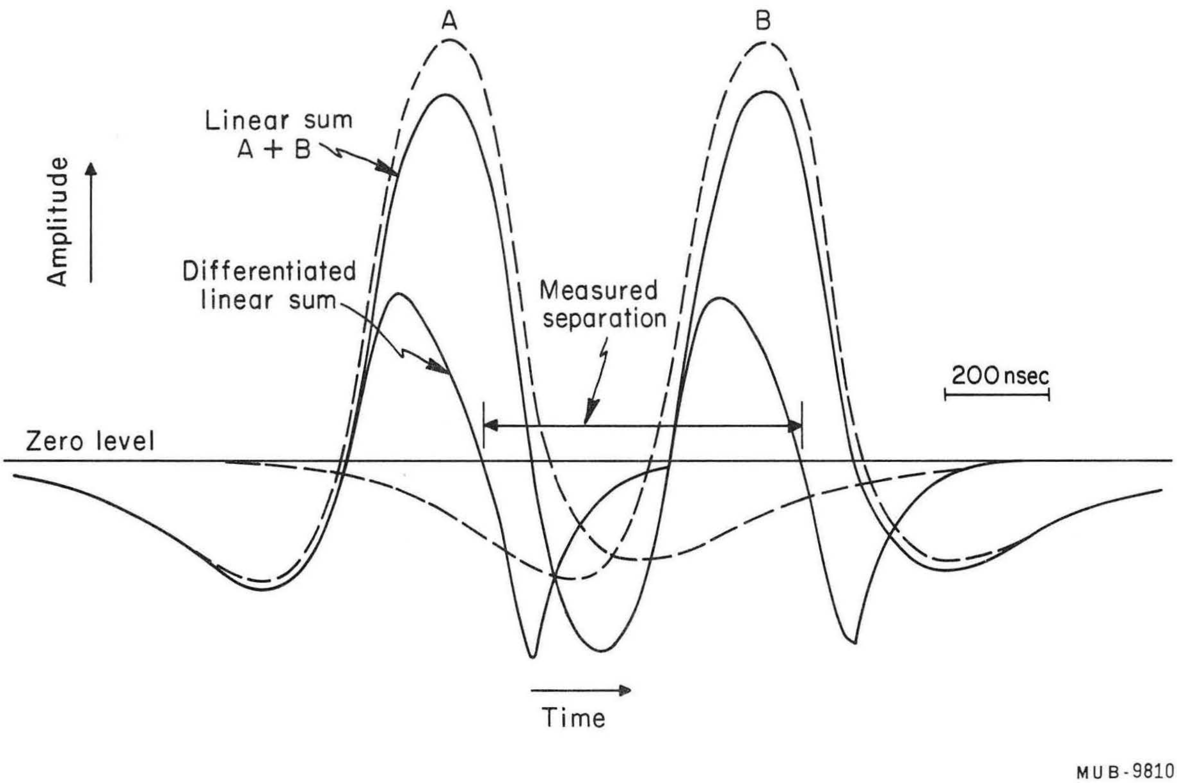
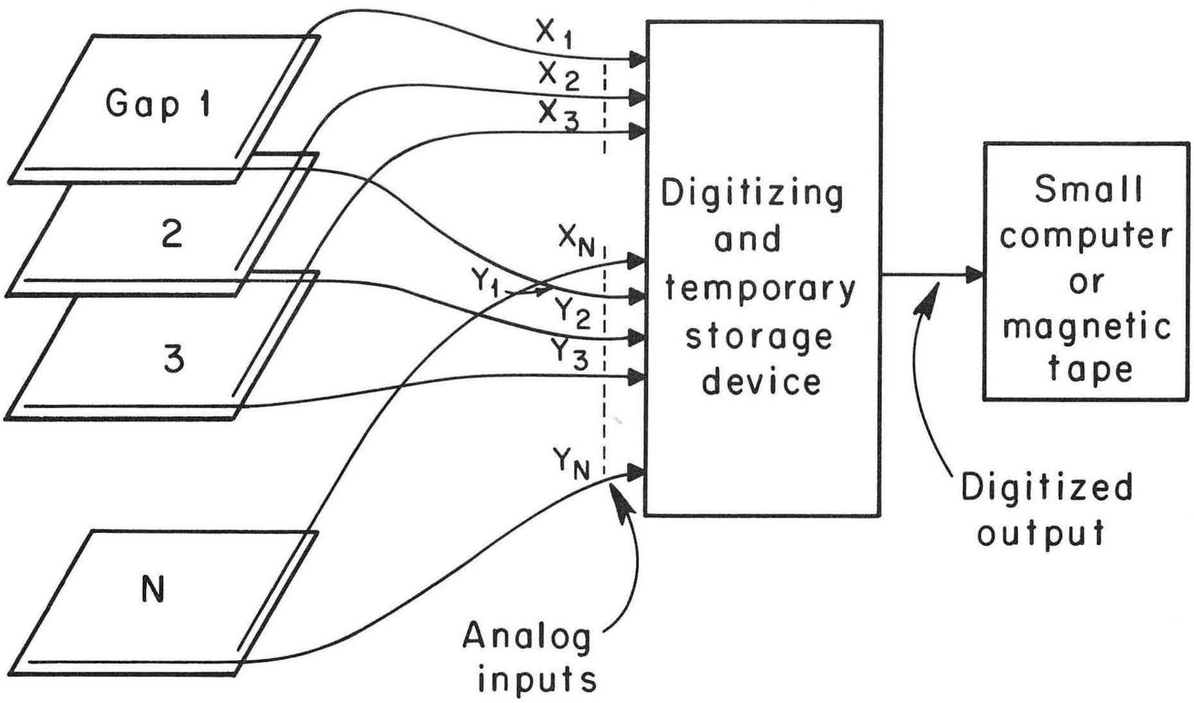


Fig. 8. Construction showing the superposition of responses to currents in wires 3 mm apart. A and B are the magnetostrictive transducer responses that would result if the currents flowed entirely in each of the two wires involved.



MUB-9806

Fig. 9. Parallel mode of connecting transducer outputs to the digitizing and temporary-storage device.

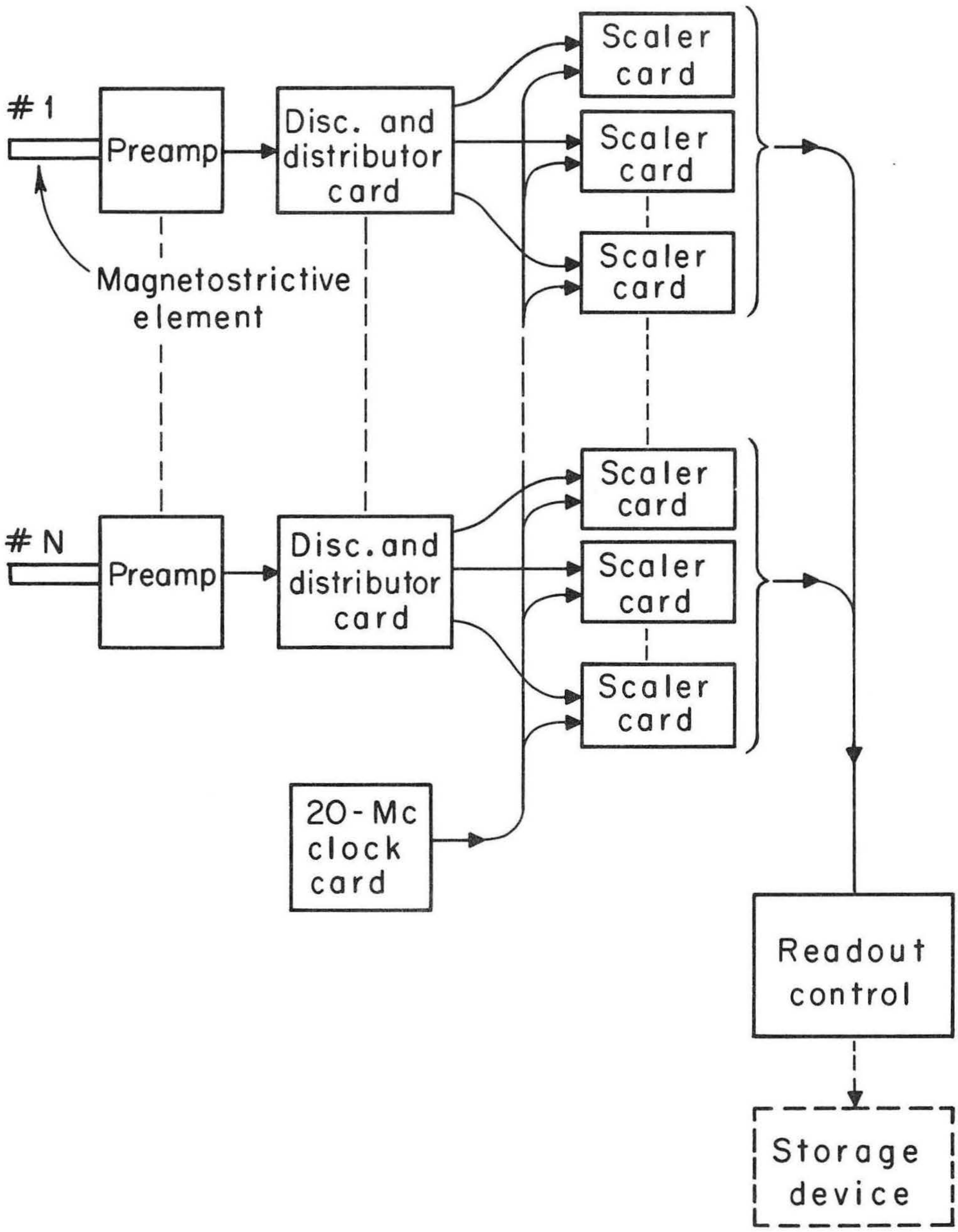


Fig. 10. Block diagram of a recording system built up from the integrated-circuit scaling components.

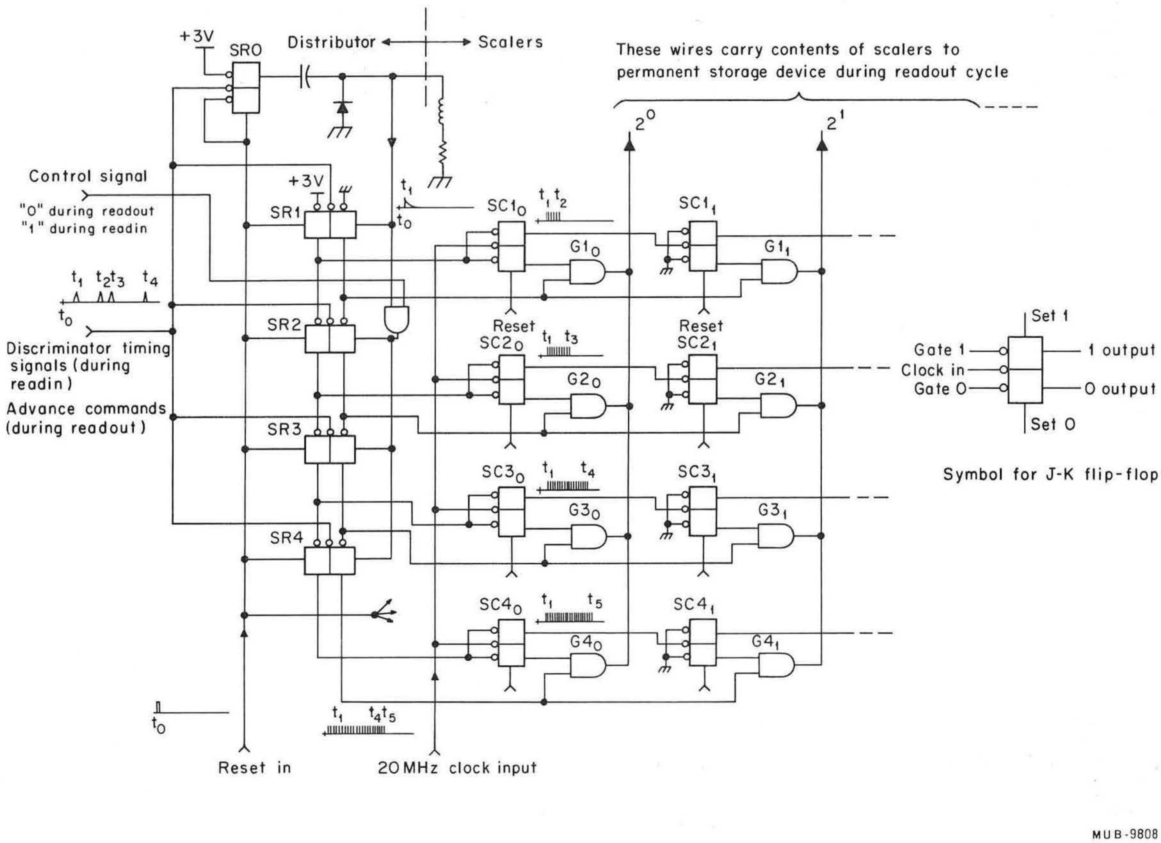
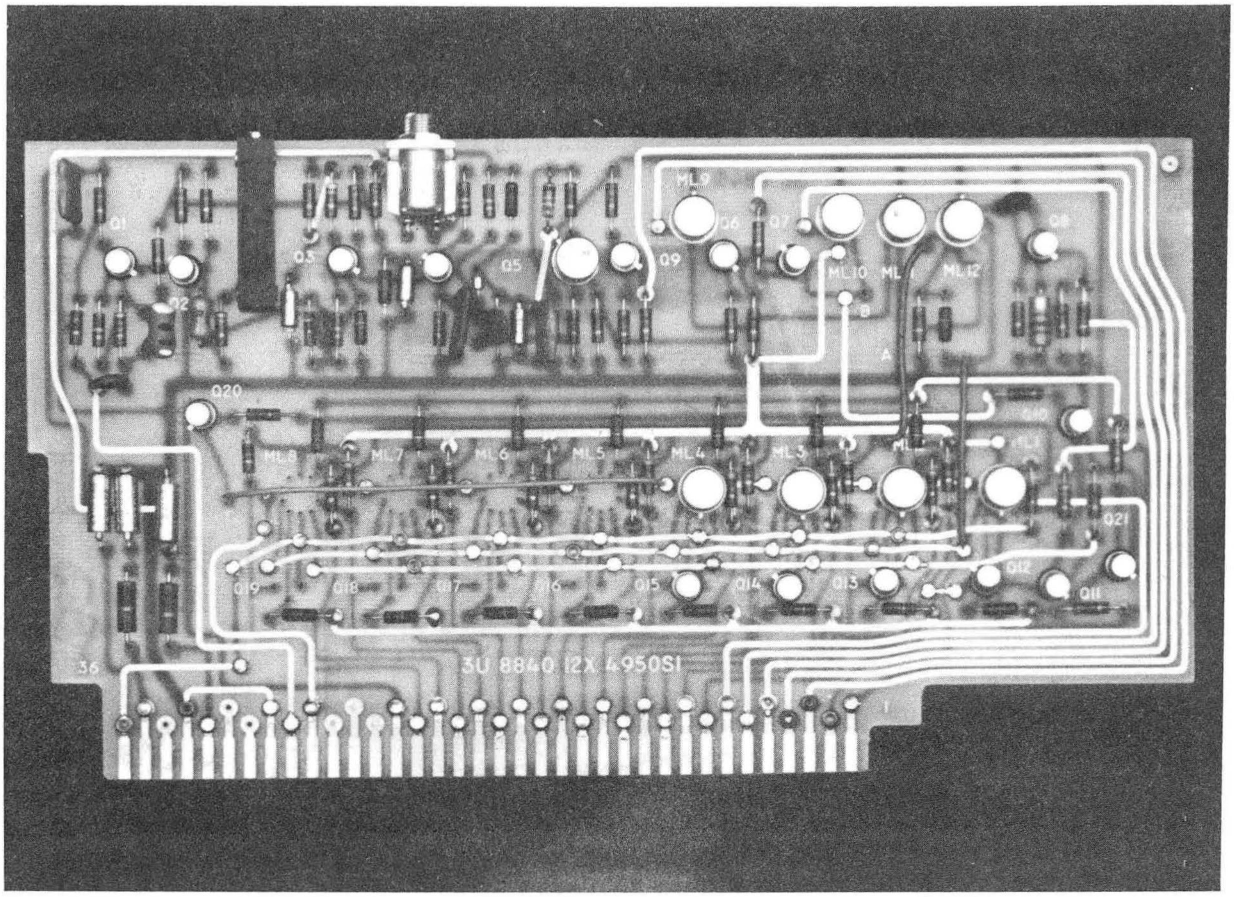
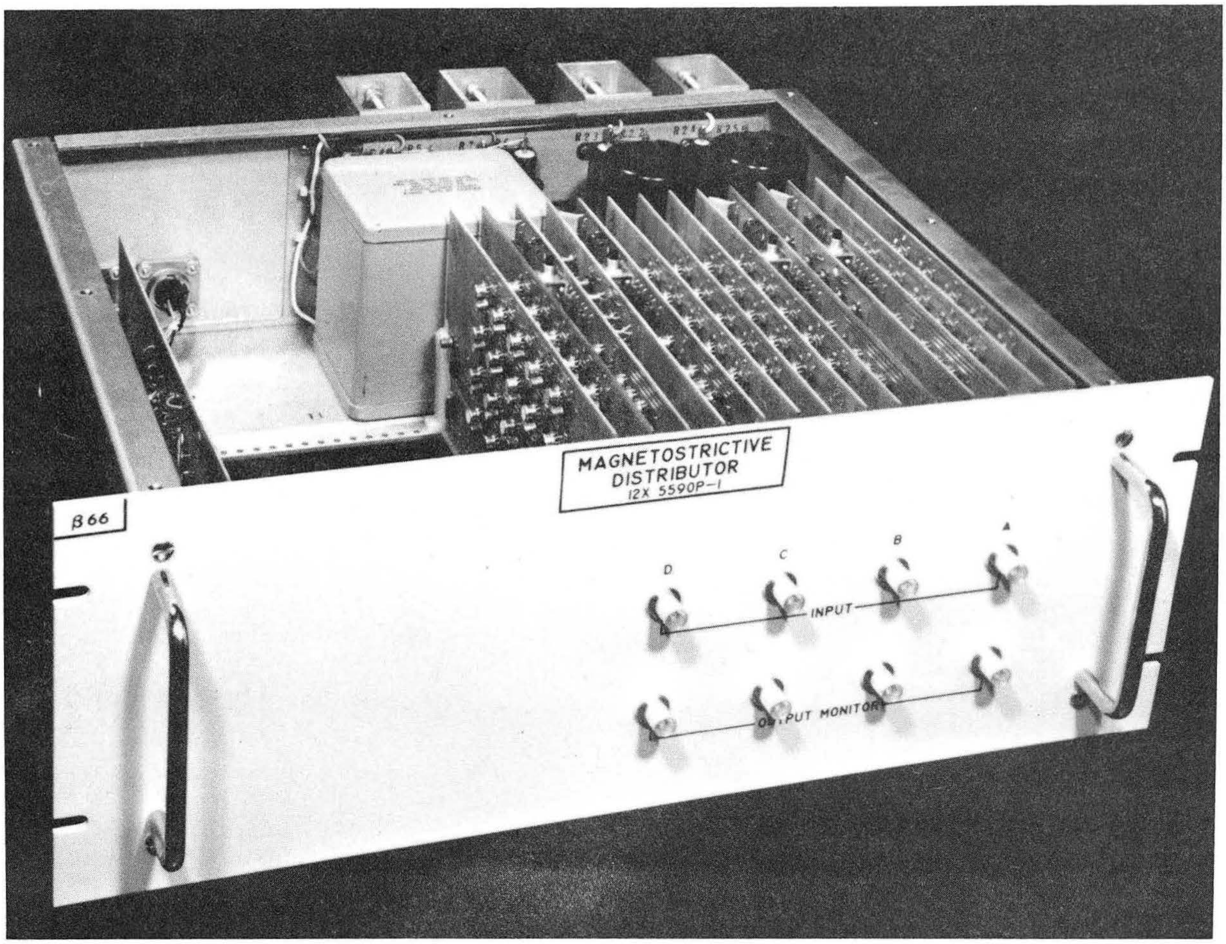


Fig. 11. Simplified block diagram showing the interrelation between the distributor and the scalers.



ZN-5400

Fig. 12. The printed card showing the distributor circuitry.



ZN-5401

Fig. 13. A drawer containing cards which hold four distributors and 16 scalers. This drawer can digitize and temporarily store the locations of four sparks in each of four spark chamber planes.