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Introduction

This paper is a brief description of the electrical system of the Astron injector. The Astron concept, a part of Project Sherwood, is a scheme for thermonuclear fusion using relativistic electrons. The idea requires a parallel, high-current beam of energetic electrons that is uniform in cross section. The ideal would be a several million-volt pulsed electron beam of 100 amperes in 1-in. diameter.

Electron Gun

The electron gun is a self-supporting structure with eight electrodes, a cathode, a heater, and a grid (see Fig. 1). The cathode has a radius of curvature of about 12 ft, but because of space-charge forces, the electron beam diverges slightly, and becomes almost parallel at the focus. The focus is about 5 ft below the exit of the electron gun, and is the point of injection into the next part of the Astron machine. The cathode is of the nickel-matrix type and is 6-in. in diameter. It was constructed by Eitel-McCullough of San Bruno, California, and is one of the largest ever made. The cathode and the electrodes are a set of re-entrant concentric cylinders insulated by vacuum in the electron beam region. The cylinders are suspended from a series of rings, one above the other, and these are supported by a set of shielded alumina insulators. The shields are arranged to distribute the gradient evenly along the insulators; there is no direct line of sight into the insulating surface, which tends to keep electrons from piling up on the insulating surface. The cathode is heated by radiation from a 4-kw tungsten heater inside the cathode cylinder, and about 1/4 in. about it.
The eight electrodes are at intermediate positions, and are arranged to minimize the edge effects on the beam.

Energy Storage

Because the electron current is from 50 to 100 amp, the gun must be powered by a low-impedance source. We planned to follow the injector with a unique system of single-turn pulse transformers to raise the beam energy to 3000 kv, and work had already begun on testing of cores for these transformers. Therefore we decided to power the electron gun from a pulse transformer with the same type of cores, and to place the transformer in the same vacuum tank as the electron gun.

Figure 2 shows the block diagram of the electrical system of the Astron injector. The pulse transformer consists of twenty large hypersil cores arranged around the electron gun. The secondary winding of the transformer is an eight-turn helical coil passing through all twenty cores. Each core has an individual two-turn primary winding, so that the composite transformer has an 80-to-1 step-up. Figure 3 shows the completed gun and transformer assembly.

Tests on one-core prototypes of the transformer indicated that it was possible to deliver square pulses, and that the input impedance was about 4 ohms per core. The composite transformer required a pulse line with about 0.2 ohm characteristic impedance, a pulse length of about 0.75 μsec, and a voltage holding capability of 25 kv. Because the whole gun and pulse transformer was considered an experimental device, we did not want to spend time developing a pulse line that might be in use only a short while. Consequently, after a few tests to prove its feasibility, we made our pulse line from 120 500-ft lengths of RG-8/U cable which were folded back in the center and paralleled at the ends. This made a multiple pulse line of 240 parallel cables, each 250 ft long, which had the desired parameters. Several million pulses were delivered during the developmental period, and we lost five cables owing to breakdown of the polyethylene dielectric. These failures were attributed to the severe transients that accompanied short-circuit conditions in the electron gun.

Near the end of the developmental period we obtained some special GE capacitors 24-in. in diameter and 7-in. high, originally designed for use at 100 kv in oil. Placing four of these capacitors in a row and connecting them together with parallel-plane copper strips 24-in. wide gave us a pulse line which had about 0.4 ohm characteristic impedance, and which delivered a 1-μsec pulse of 10 kv into its characteristic impedance. Two of these lines are now in use at Livermore. Their main advantage is that they are considerably easier to handle and maintain than the rolls of cable. Figure 4 shows the rolls of cable used as a pulse line and Fig. 5 shows the capacitor pulse line.

Spark-Gap Switch

Energy is stored in the pulse line at voltages as high as 25 kv. Switched energy is being delivered to the 0.2-ohm load at voltages up to 12.5 kv, so that the switch must handle up to 60,000 amp with a minimum of jitter. We designed a multiple, three-ball spark gap based on information from Stanford University on spark-gap switches. Figure 6 shows this unit. It consists of four paralleled spark gaps in a soundproof box. The walls of the box are layers of steel and glass fiber, and reduce the sound level by about 60 db. Air is blown through to cool the gaps, and to carry away the gaseous products of the discharge. The electrodes consist of graphite cylinders 2-in. in diameter. (The ends were originally convex, but after several million sparks the positive electrode became slightly concave). Because the electrodes are carbon, there is no sputtering or transfer of electrode material to the walls of the box; instead, there is a slow erosion of the electrode, in which the carbon is oxidized to CO_2. The center electrode is held at 2/3 of the voltage of the positive electrode, To fire the gap, the center electrode is pulsed negatively to approximately 30 kv. The gaps are illuminated by a small mercury-arc lamp, and gave us a typical jitter of less than 0.06 μsec.

The back wall of the spark-gap chamber was made of lucite and glass fiber. Behind this wall is an oil-filled box with voltage-dividing resistors, trigger transformers, and copper busses to which the 240 cable ends are attached.

Pulse Transformer

Most of our tests were performed on several test cores with tightly coupled secondaries, and the data agreed with the calculated values (see Appendix 1). The secondary winding was designed to be self-supporting to avoid insulator problems, and consequently could not have many turns. The final design used an eight-turn secondary, which coupled all the cores in the composite transformer, making a rather loosely coupled secondary. The primaries were tightly coupled two-turn aluminum sheets.

The core material was 2-mil Silectron wound into a core of 2-by-4-in. cross section. The window opening was 18 by 34-in. to allow adequate spacing for holding voltage in the vacuum. With an 89% space factor, this gave about 1780 laminations. We had difficulty obtaining cores of the size we needed, and the cores that were supplied were guaranteed for only 0.8 volt per lamination. When the cores were pulsed in vacuum, at voltages greater than 2.85 kv per turn bright points of light on the edges of the cores indicated breakdown. Even though the energy lost in these sparks was negligible the sparks were very troublesome, because they tended to trigger sparks on the electron gun structure which pitted the voltage-holding surfaces. The operating voltage of the pulse transformer is determined by the sparking rate; as the voltage is increased the sparking rate increases from several times per hour to several times per second. The latter is clearly unacceptable, because in a few minutes the polished surfaces would be destroyed.

The composite pulse transformer behaved much differently from the single-core prototypes. Before the transformer was completed we built a small analog of the equivalent circuit and excited it with a multivibrator to simulate the pulse length and impedance of the pulse line. This analog (shown in Fig. 7) enabled us to study effects of changes in stray capacity and load impedance, and to predict the expected wave shapes and voltages. Figure 8 shows some of the wave forms.

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[1] Ferd Voelker, Analysis of Iron Cores Driven with Fast Pulses and High Voltages per Turn, UCID-827, Dec. 1958.

We were disappointed by the prediction of the behavior of the transformer because we had not realized how much the added capacitance was going to affect the pulse shape. The completed transformer behaved very much as predicted, and we resorted to stagger firing of the primary to lenthen the top of the pulse. This was done at the expense of output voltage, and about the best we obtained was a 0.4-μsec interval flat to ± 3%. The input voltage had to be increased about 20% to maintain the same secondary voltage.

Performance

At the 675-kv level the gun delivered 56 amp of electrons into a Faraday cup 5 ft below the grid. The divergence of the beam was inferred from shadows cast by wires of known diameter on a silvered glass surface: the electron beam pitted the surface that was not shadowed, allowing us to measure the diameter of the shadow. The diameter of the beam was measured by placing a lead foil in the electron stream: the beam melted a hole in the lead foil where the energetic electrons hit (see Fig. 9). The beam is less than 1-7/8-in. diameter and has less than 0.005 radian divergence at the focal point. The machine is now in operation at Livermore, at approximately 700 kv, as the injector for the second part of the Astron machine now being developed. It has been operated as high as 750 kv, but at this level the sparking rate was several times a minute.

Acknowledgment

The development of this invention by Nicholas Christofolis was done jointly the author and Kenneth W. Ehlers, Physicist on the project.

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

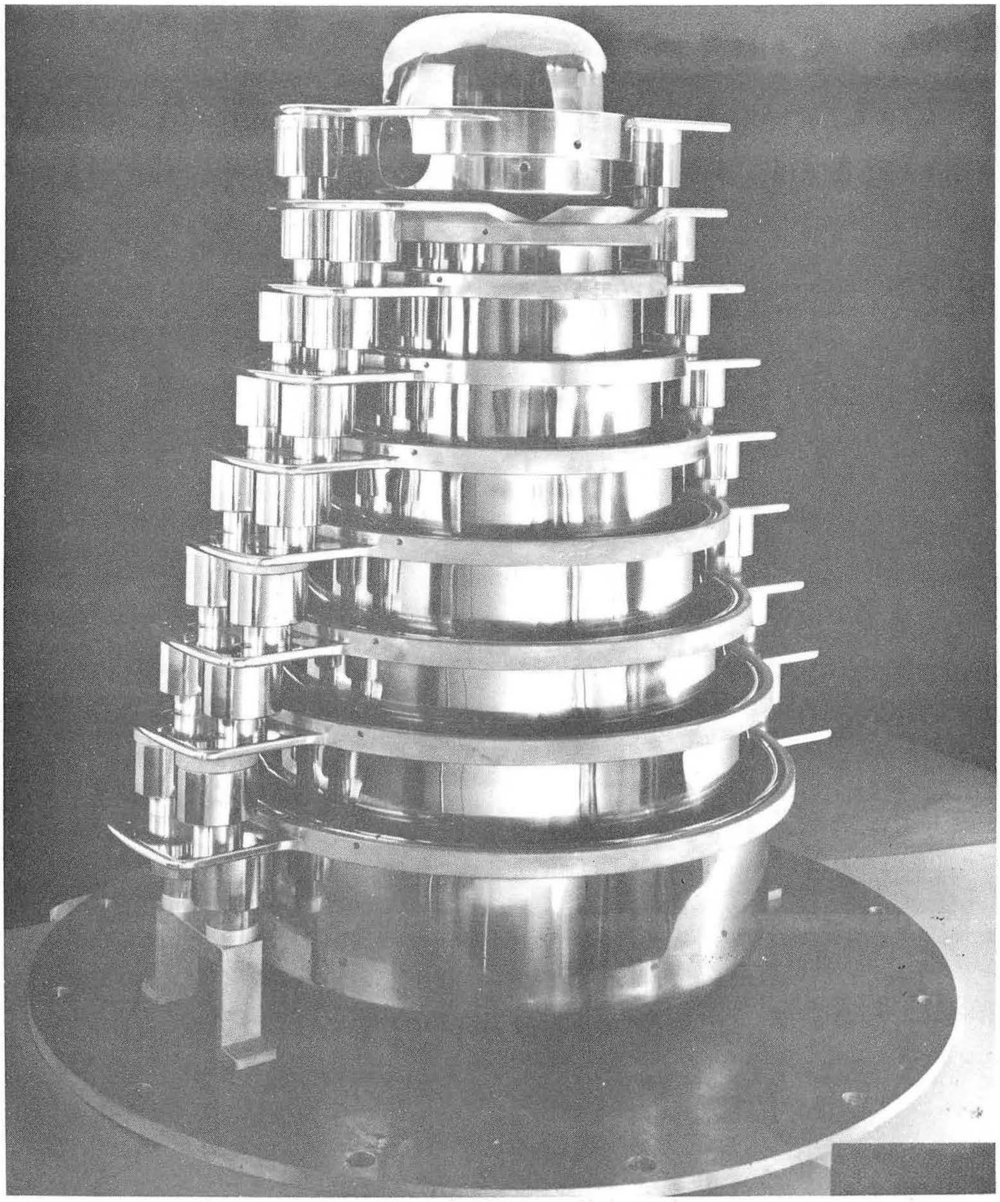

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Fig. 1. Electron gun.

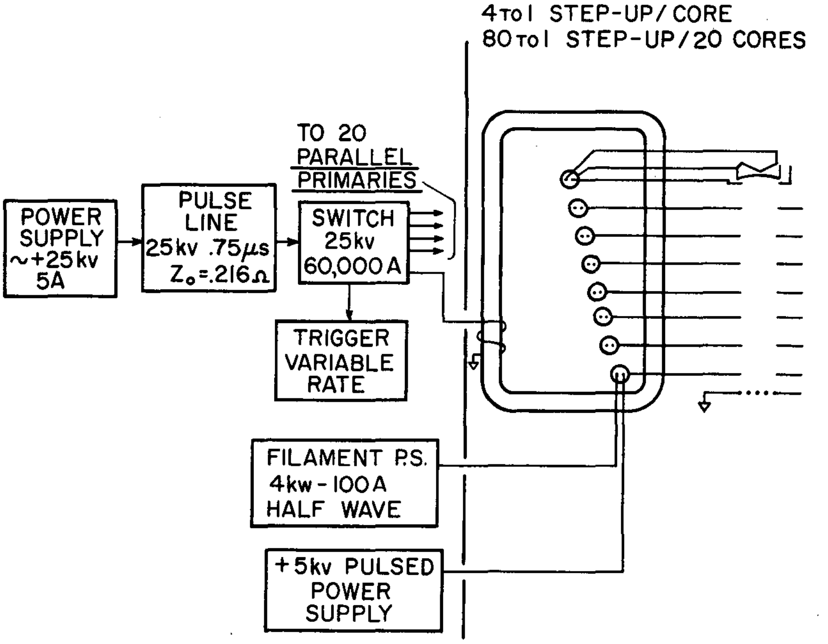

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Fig. 2. Block diagram.

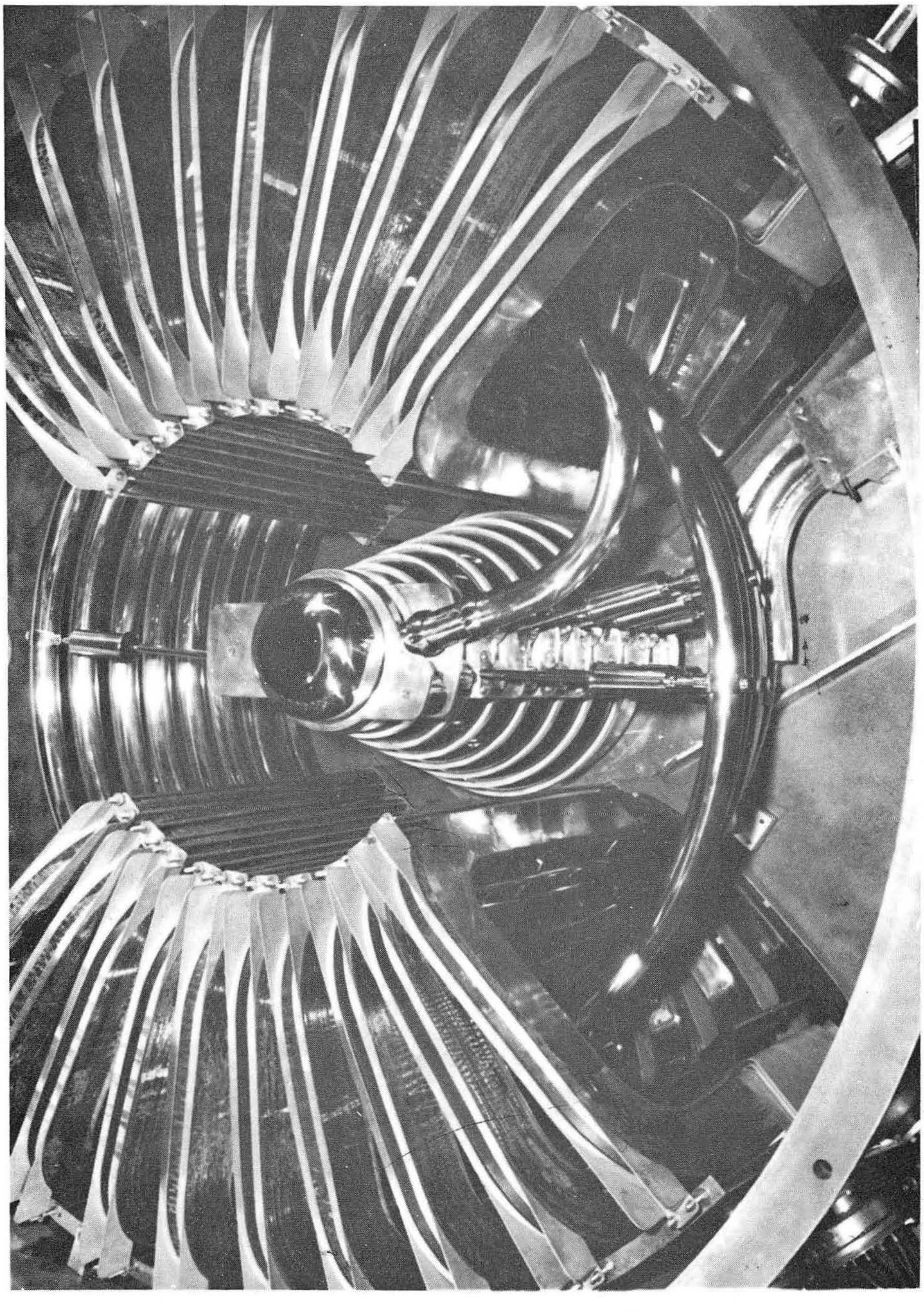

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Fig. 3. Pulse transformer and electron gun.

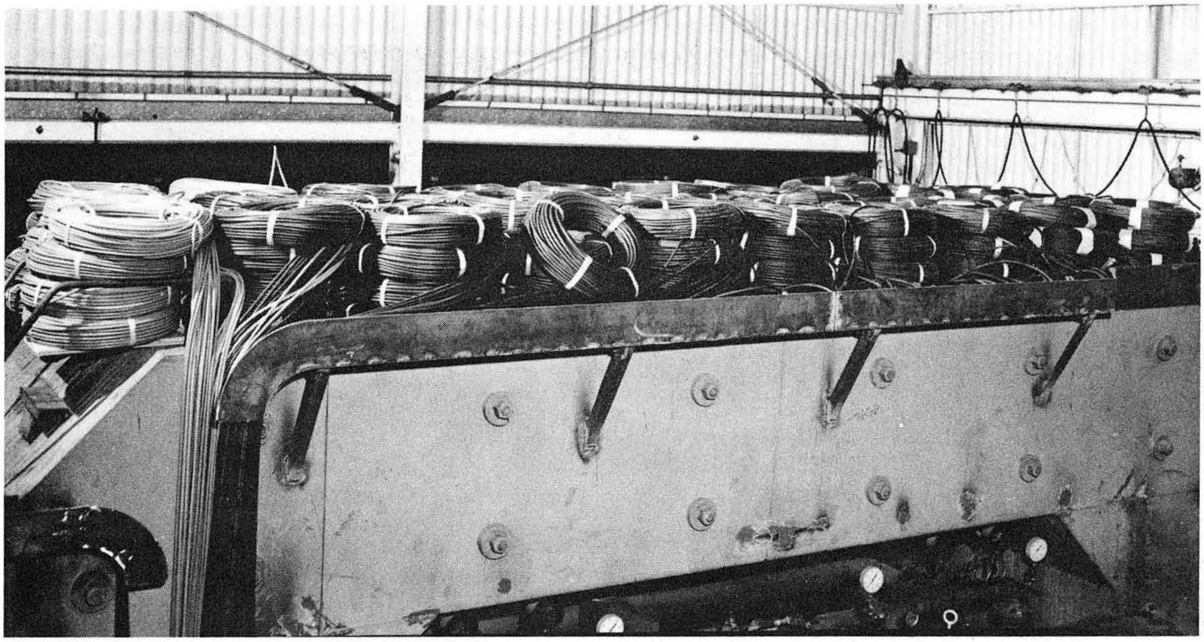

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Fig. 4. Pulse line cable.

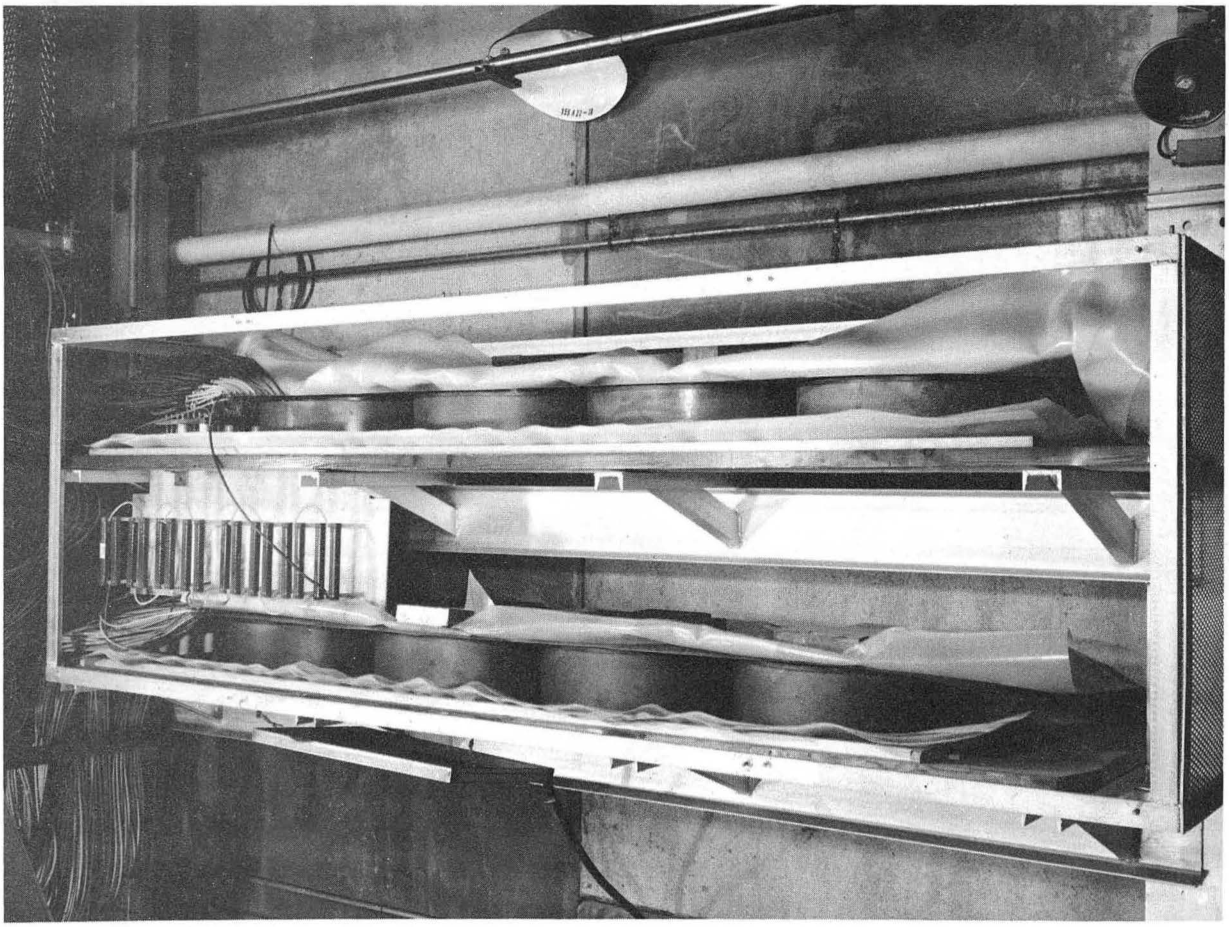

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Fig. 5. Pulse line capacitor.

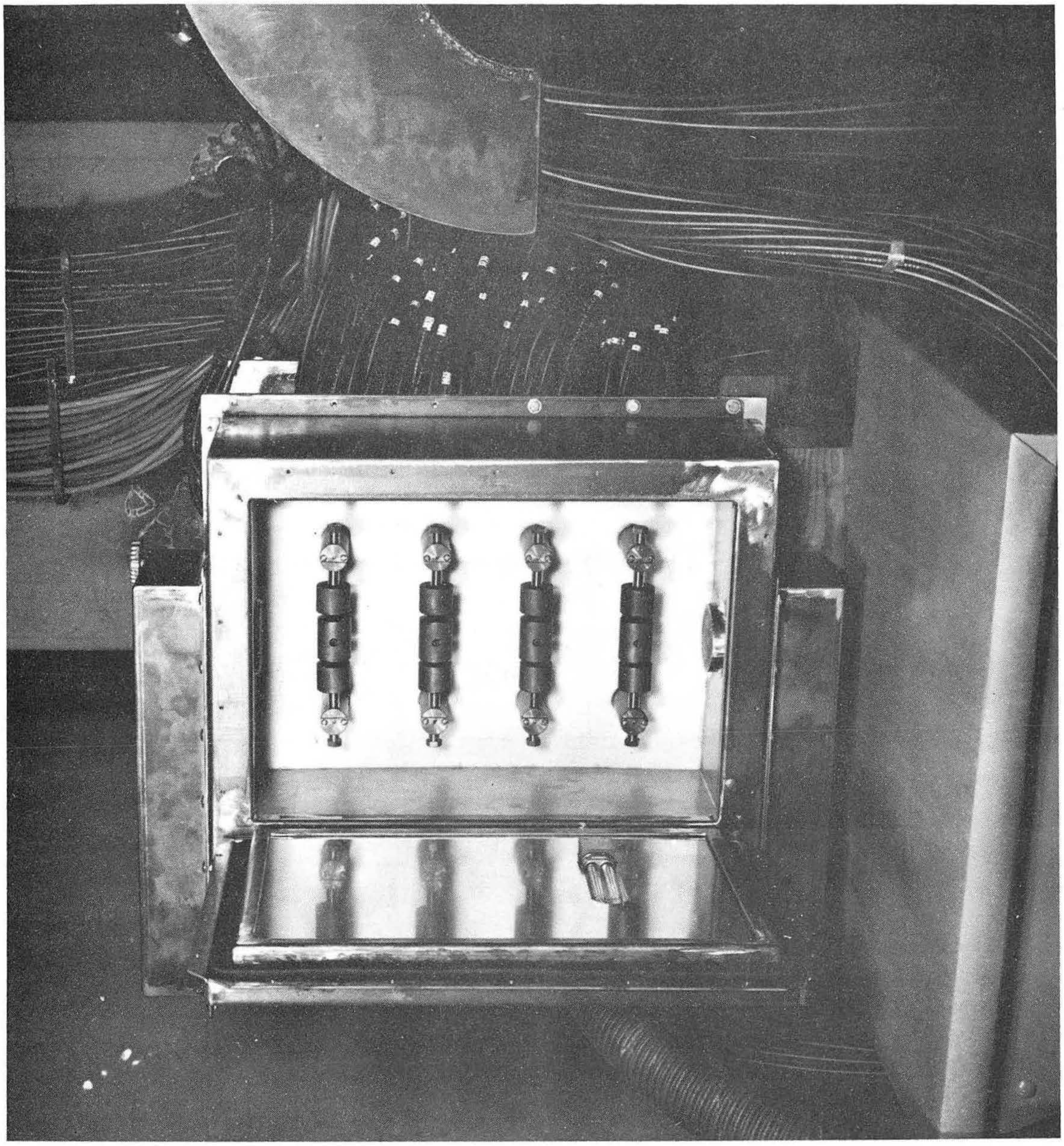

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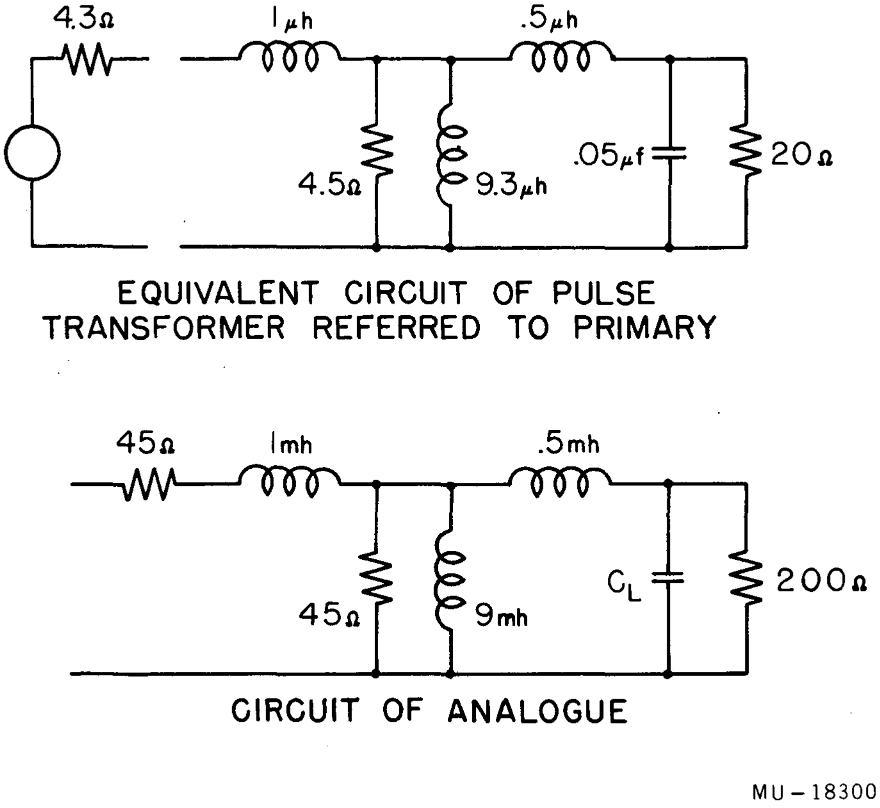
Fig. 6. Spark gap switch.



EQUIVALENT CIRCUIT OF PULSE TRANSFORMER REFERRED TO PRIMARY

CIRCUIT OF ANALOGUE

Fig. 7. Picture and circuit of analog.

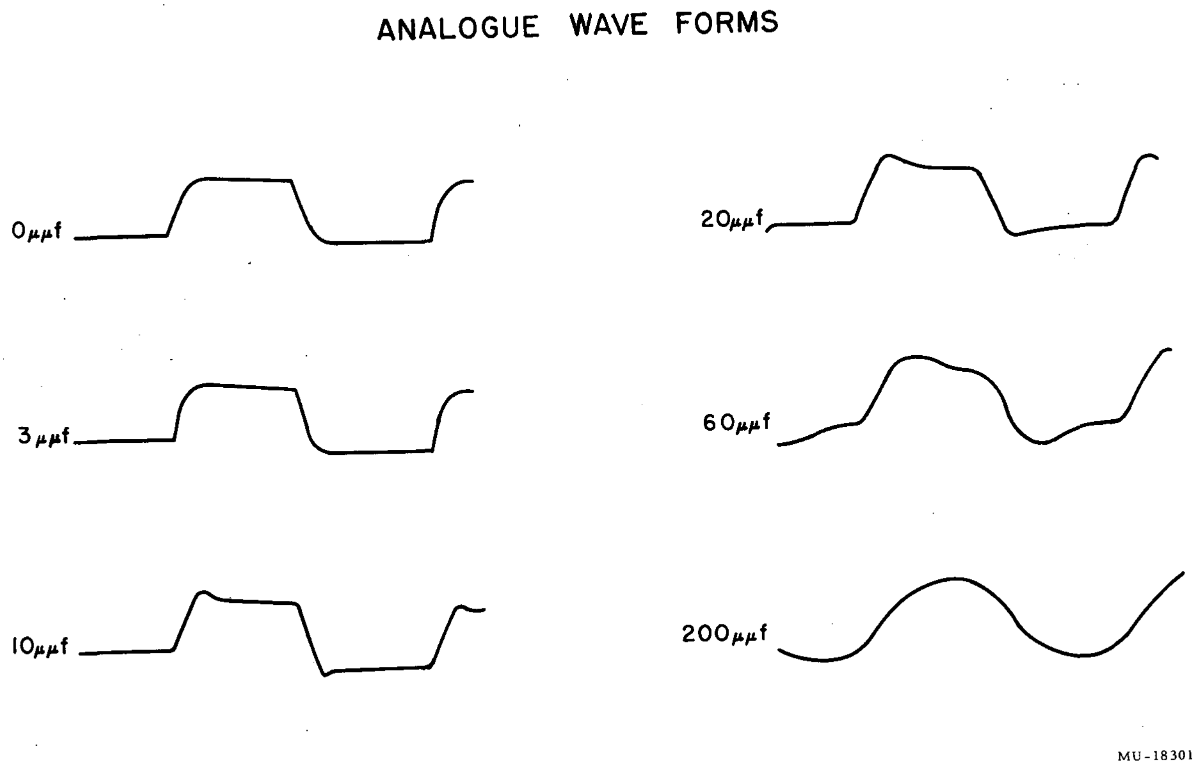


Fig. 8. Analog wave-forms.

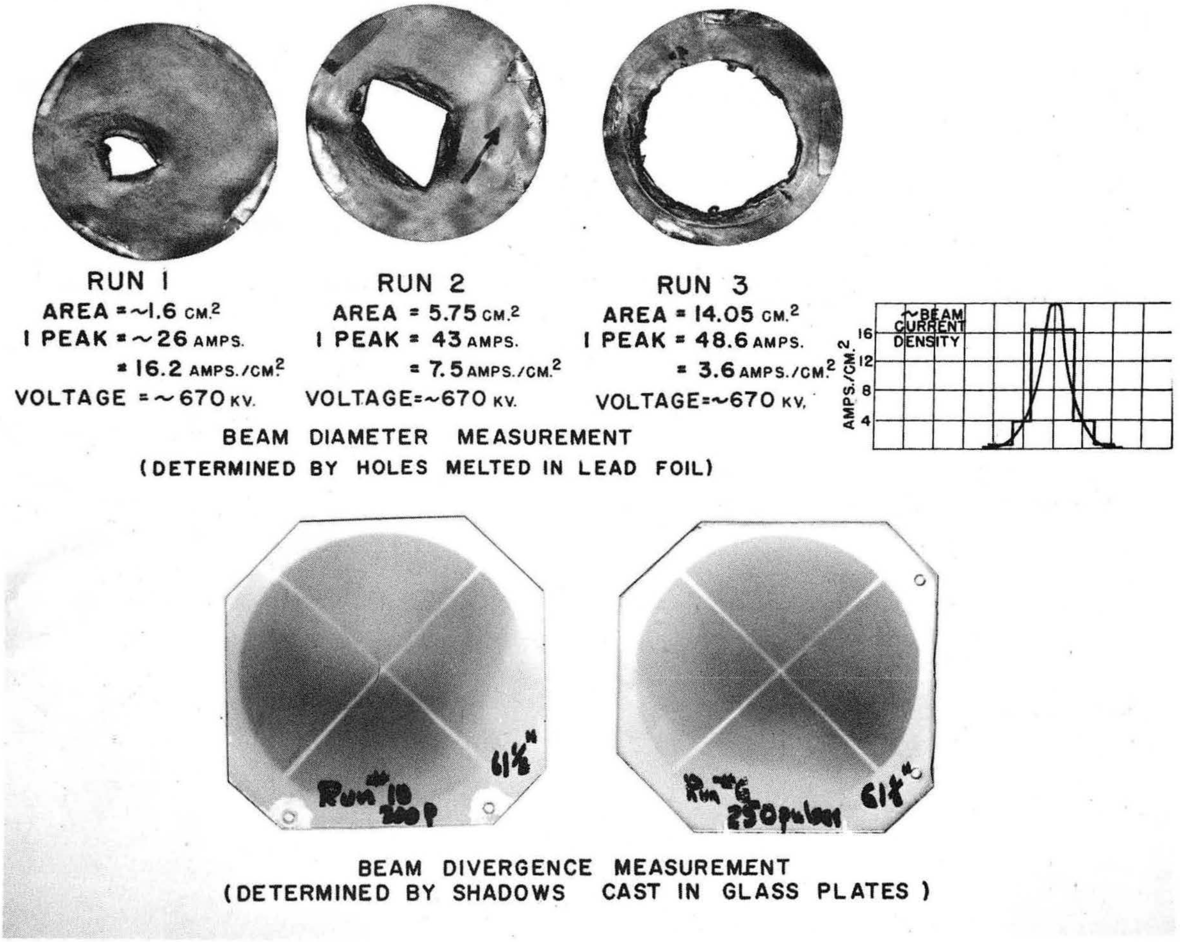


Fig. 9. Holes and shadows of targets.