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SC-DR-70-872

REBA, A PULSED ELECTRON BEAM GENERATOR

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December 1970

ABSTRACT

A new electron beam generator, called REBA (Relativistic Electron Beam Accelerator), was designed and constructed. REBA produces 43 kA beams of 3.2 MeV electrons in 70 nsec pulses at a rate of up to 40 shots per day. A unique feature of REBA is that a single Marx generator can pulse charge either of two Blumlein transmission lines and thus provides two independent sources of electrons for experimenters. The research and design considerations and the preliminary operating parameters of REBA are discussed in this report. Preliminary electron beam measurements are also presented.

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REBA, A PULSED ELECTRON BEAM GENERATOR

Introduction

In order to accommodate an increasing demand for experimental time on Hermes I, an additional electron beam generator or a replacement for Hermes I with a greater capacity for users was needed. The requirements were that the new generator be similar to Hermes I in impedance, energy storage, and output characteristics. The space available to house the facility was the portion of Building 6596 (Sandia Laboratories) shown in Fig. 1; the rest of the building being occupied by the Hermes II facility.

To meet the space requirements and facilitate operations and maintenance, a single Marx generator with a dual electron beam output was selected. The Hermes I Marx generator, with proven reliability (10,000 firings), and the Hermes output tube were used to reduce the development time needed to produce an operational machine.

Fig. 2 is a cutaway drawing of the new machine called REBA (Relativistic Electron Beam Accelerator). The Appendix lists the physical and electrical parameters for REBA.

Before discussing the design and output characteristics of REBA, a brief discussion of the operation of an electron beam generator of this type will be made to demonstrate the operation of REBA.

Fig. 3 diagrams a simplified pulsed electron beam generator utilizing a Blumlein transmission line[1] as the high speed energy store. It consists of a Marx generator, a Blumlein transmission line, and an output tube. Energy is transferred

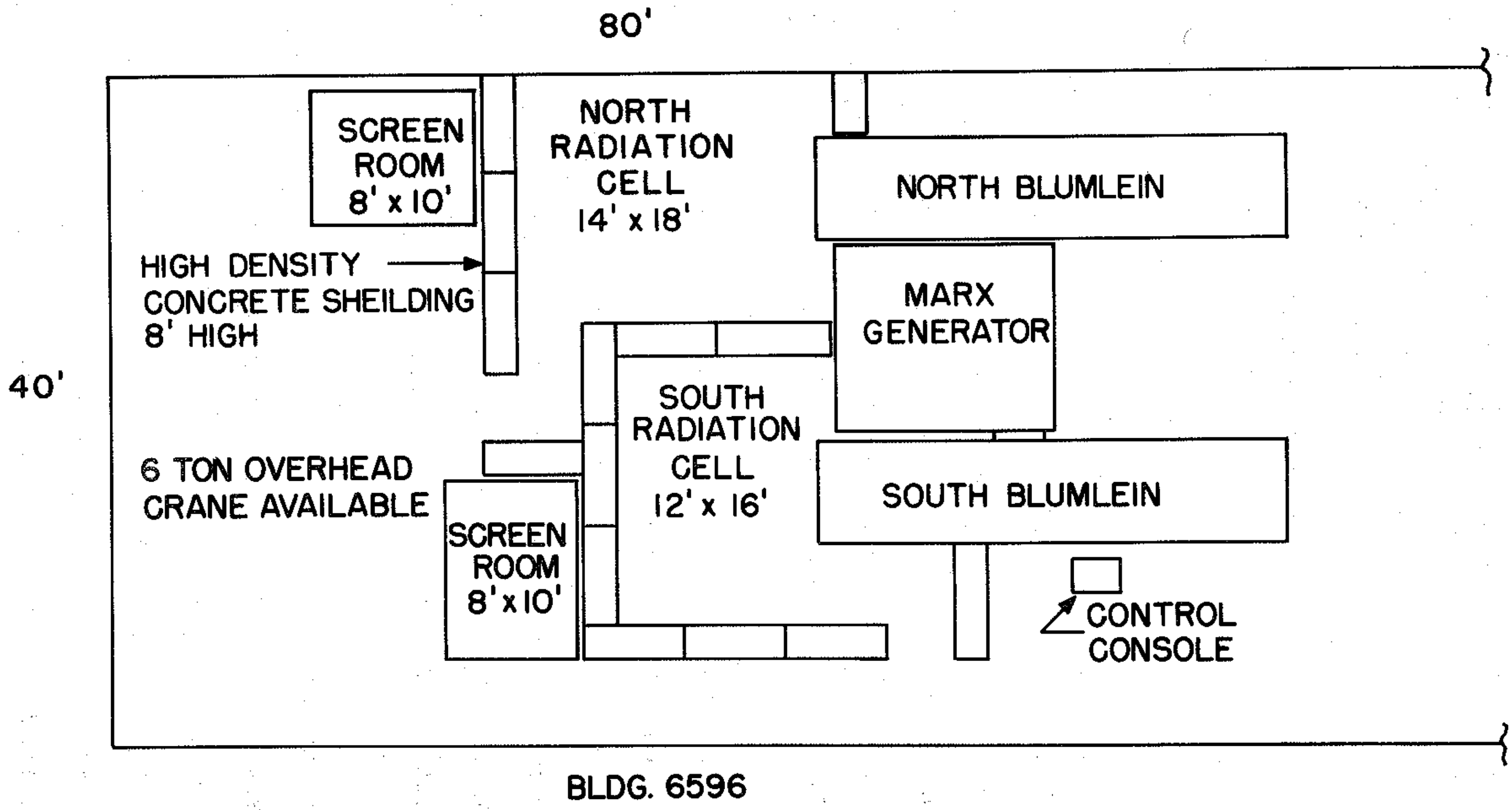
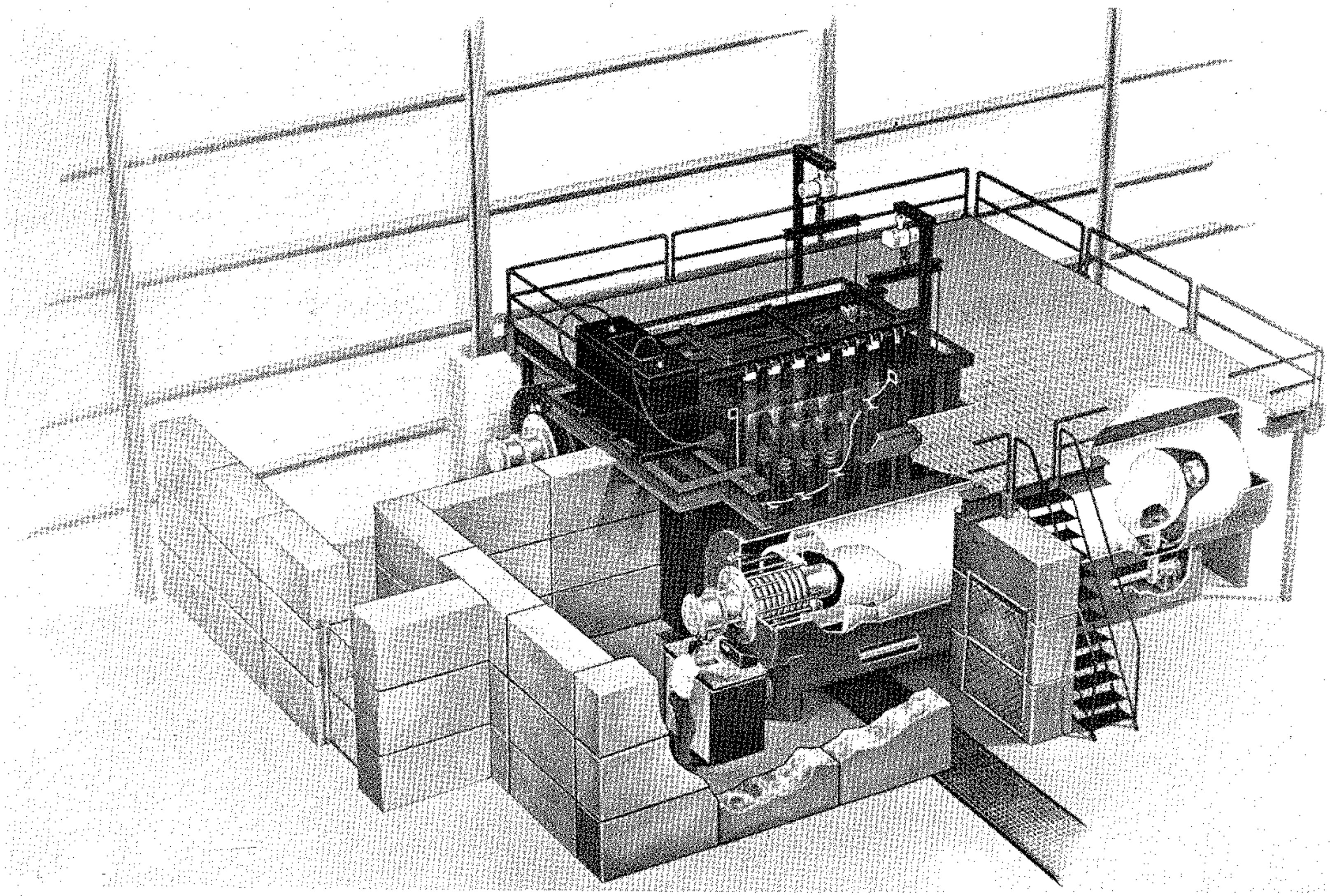


Fig. 1. Physical Layout of REBA Facility



REBA

Fig. 2 Artist's Drawing of REBA

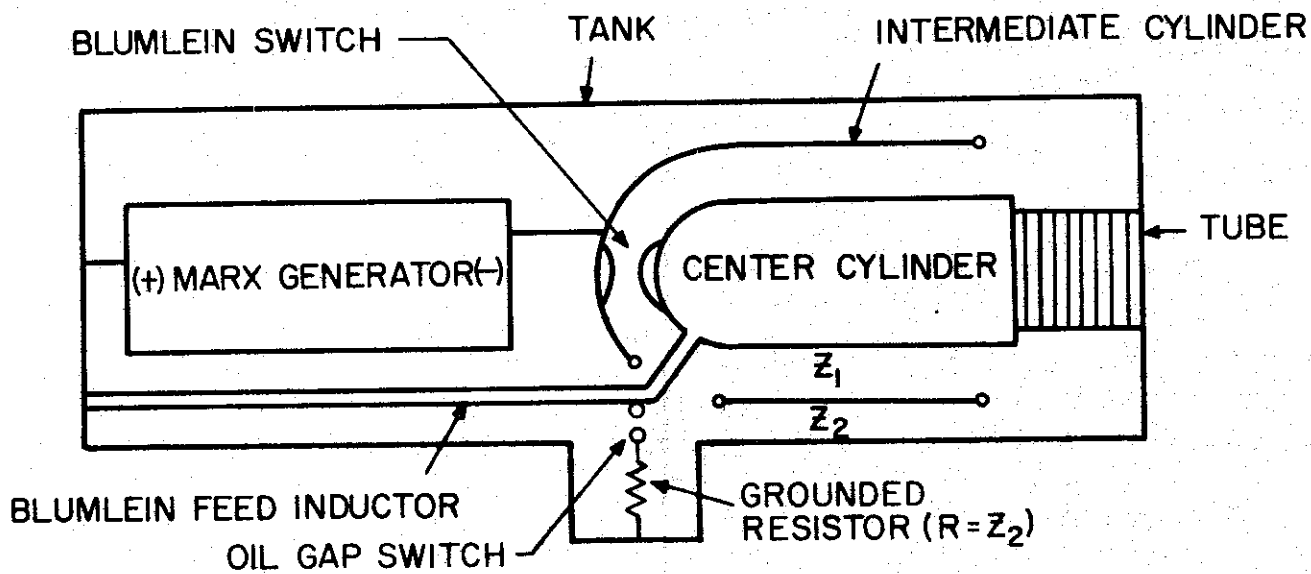


Fig. 3. Simplified Blumlein Machine

from the Marx generator to the Blumlein transmission line which, in turn, serves as a fast discharge, low-inductance energy source for the output tube. Transformer oil is used as the insulating dielectric.

The Marx generator consists of a bank of capacitors charged in parallel and discharged in series by means of spark gap switches.[2] The Marx generator pulse charges the intermediate cylinder, Fig. 3, to a negative potential. Both the outer cylinder (the tank wall) and the center cylinder (by means of an inductor) remain at ground potential during the charging of the intermediate cylinder.

Fig. 4 shows an equivalent circuit for the Marx generator and Blumleins during the charging of the intermediate cylinder. For this circuit,

L_m = total Marx generator inductance

C_m = total Marx generator capacity

R_s = total Marx generator series resistance

R_p = equivalent Marx generator parallel resistance

C_1 = capacity between intermediate and center cylinders

C_2 = capacity between intermediate and outer cylinders

L_1 = Marx switch inductance

L_2 = center cylinder isolating inductance.

When the voltage on the intermediate cylinder reaches a predetermined value, the Blumlein switch closes by self-breakdown. The voltage transient created propagates between the center and intermediate cylinders. When the voltage transient reaches the output tube end of the transmission line, a voltage is created across the tube for twice the electrical transit time of the transmission line. For a lossless system and a matched tube-to-Blumlein impedance, the tube voltage is equal to the charging voltage applied to the intermediate cylinder.

The output tube is an evacuated, insulating chamber with a field-emitting cathode and a "thick target" anode for bremsstrahlung production, or an anode thin

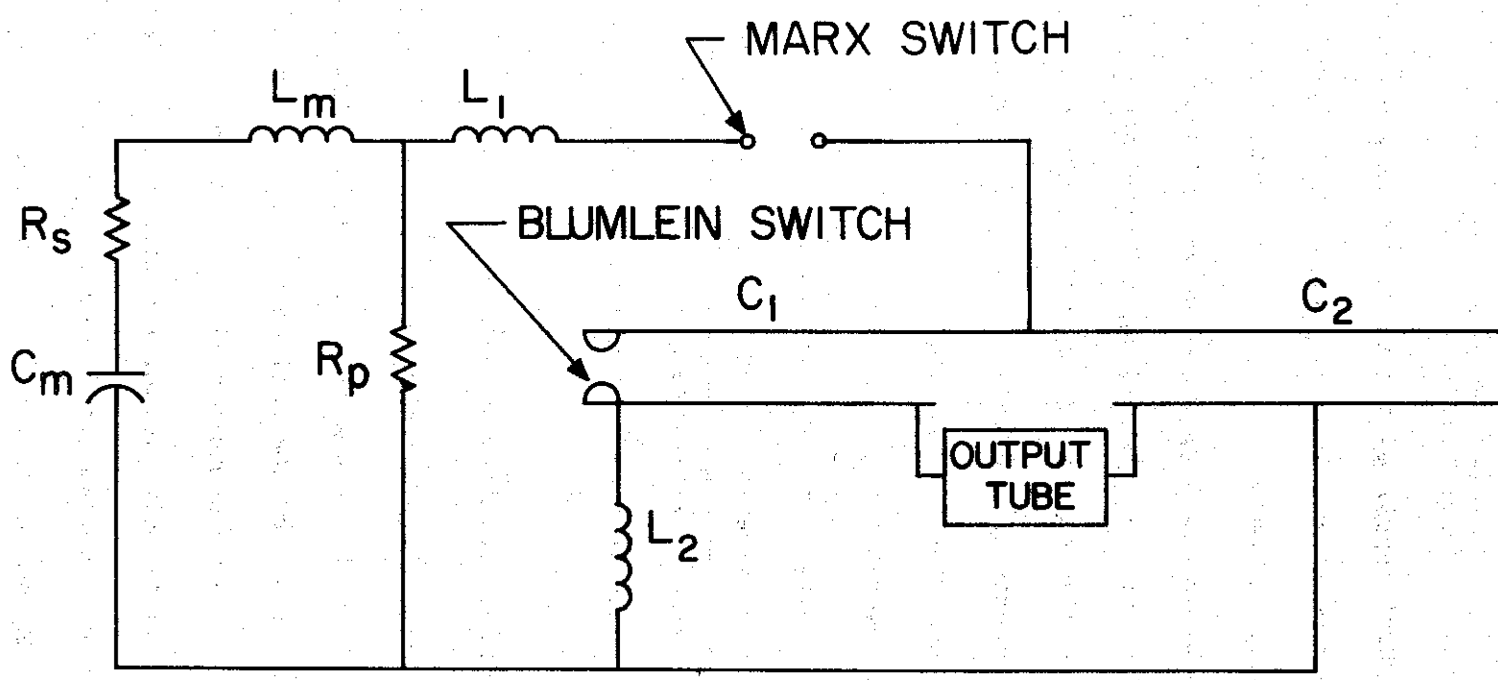


Fig. 4. Equivalent Marx-Blumlein Charging Circuit

enough to allow electrons to pass through it with minimal loss if electron experiments are to be performed. In this case the electrons emerge from the tube into a drift chamber where they are drifted or focussed.

Description of REBA

Marx Generator

The Marx generator used in REBA is housed in a tank 10 feet wide, 13 feet long, and 12 feet high. It consists of 38-1/2 μF, 100 kV BICC capacitors with 19 gas spark gap switches, stores 95 kJ at full voltage (100 kV), and has an output capacity of 13.1 nF. Fig. 5 shows a schematic diagram of the generator; Fig. 6 is a photograph of the assembled generator. The resistors interconnecting the capacitors are made of polyvinyl chloride tubing filled with a copper sulfate solution. The ground resistors are each ~~100~~ 10 kΩ and the charging resistors are each ~~10~~ 1.2 kΩ. The Marx generator is d-c charged with a variable ± 125 kV, 30 mA power supply that can be operated manually or automatically. The typical charging time (to 65 kV) is 1 minute.

Corrections in copy received 6 Mar 73

A study of Marx generators[3] yielded the particular geometry of this generator which has a fast running time (2 μsec) and a wide range of firing voltage (40 kV to 100 kV).

The spark gap shown in Fig. 7 is used in switching the Marx generator from a parallel to a series configuration. Tests were performed to determine a suitable spark gap material.[4] A tungsten-copper-nickel alloy, commonly called heavy metal (89% W, 7% Cu, 4% Ni), was selected for its resistance to arc erosion. The spark gap geometry was determined using an electrolytic tank plotter. The shape selected gave a uniform electric field over a 1.5 inch diameter circle at the end of the electrode. Fig. 8 shows the breakdown characteristics of the spark gap using a fill gas of 79 percent dry nitrogen - 21 percent dry oxygen.

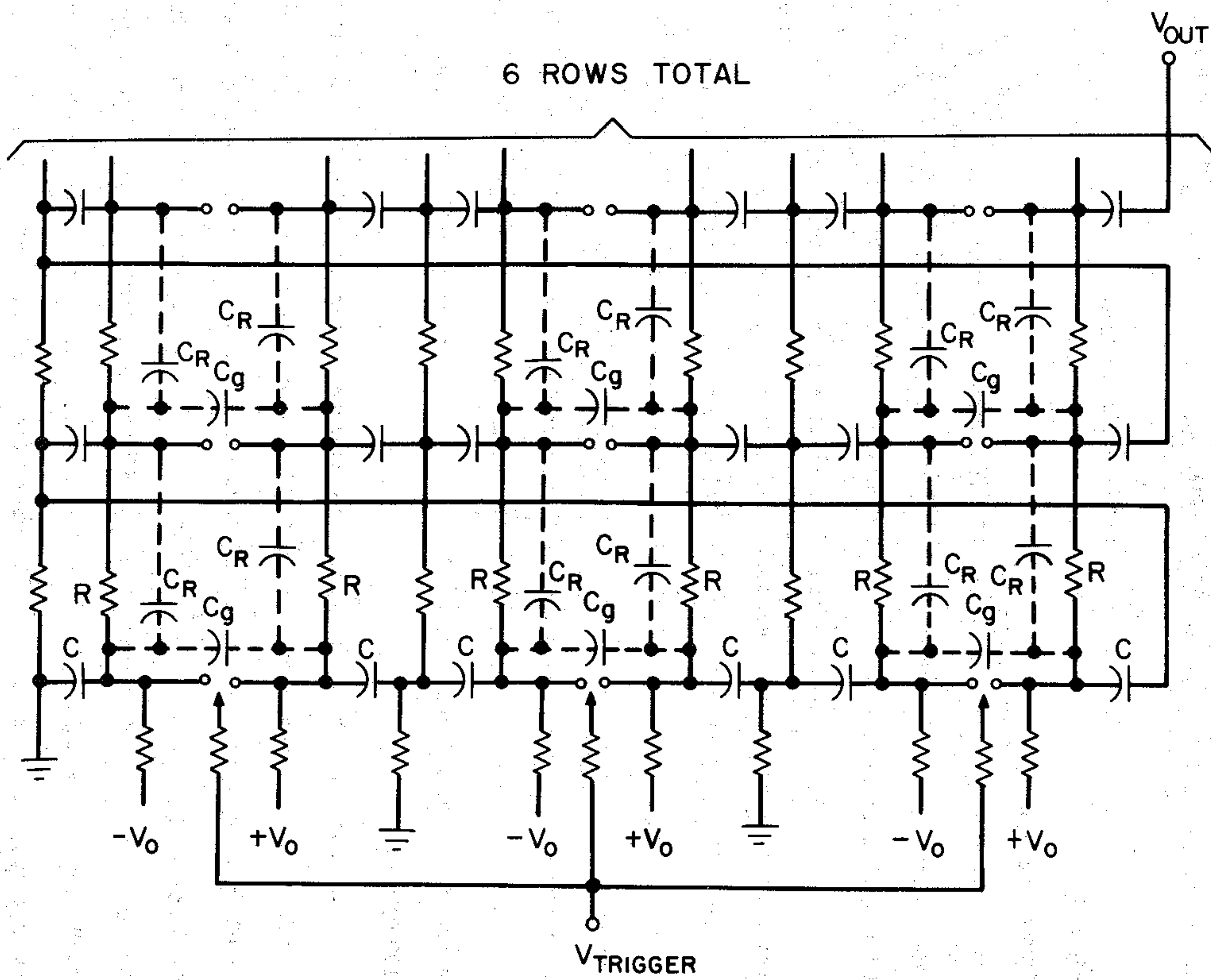


Fig. 5. Marx Generator Circuit

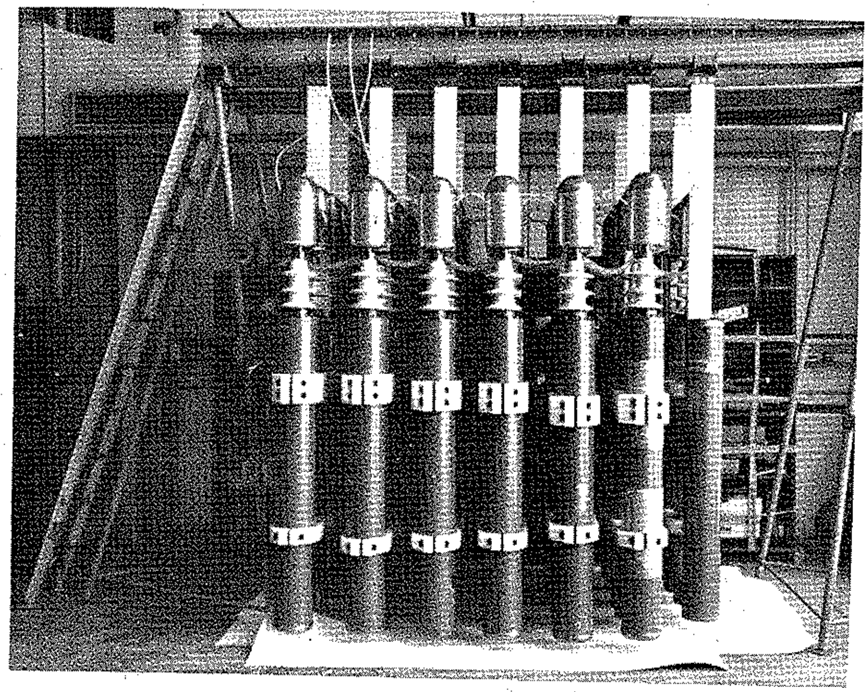


Fig. 6. REBA Marx Generator

The first three spark gaps in the generator are triggered by the circuit shown in Fig. 9, and the remainder of the gaps self break down by means of voltage transients generated within the Marx generator.

The pressure in the gaps is usually adjusted such that at a given charge voltage, the voltage across the gap is 60 percent of its self-breakdown value. This allows operating the generator with few prefires. It does, however, cause longer Marx generator running time and a larger jitter in the running time.

Finally, the Marx generator is connected to either of the two Blumleins by means of a hydraulically operated switch located at the front of the Marx generator. This switch has an inductance of 1.8 μH and corresponds to L_1 in Fig. 4.

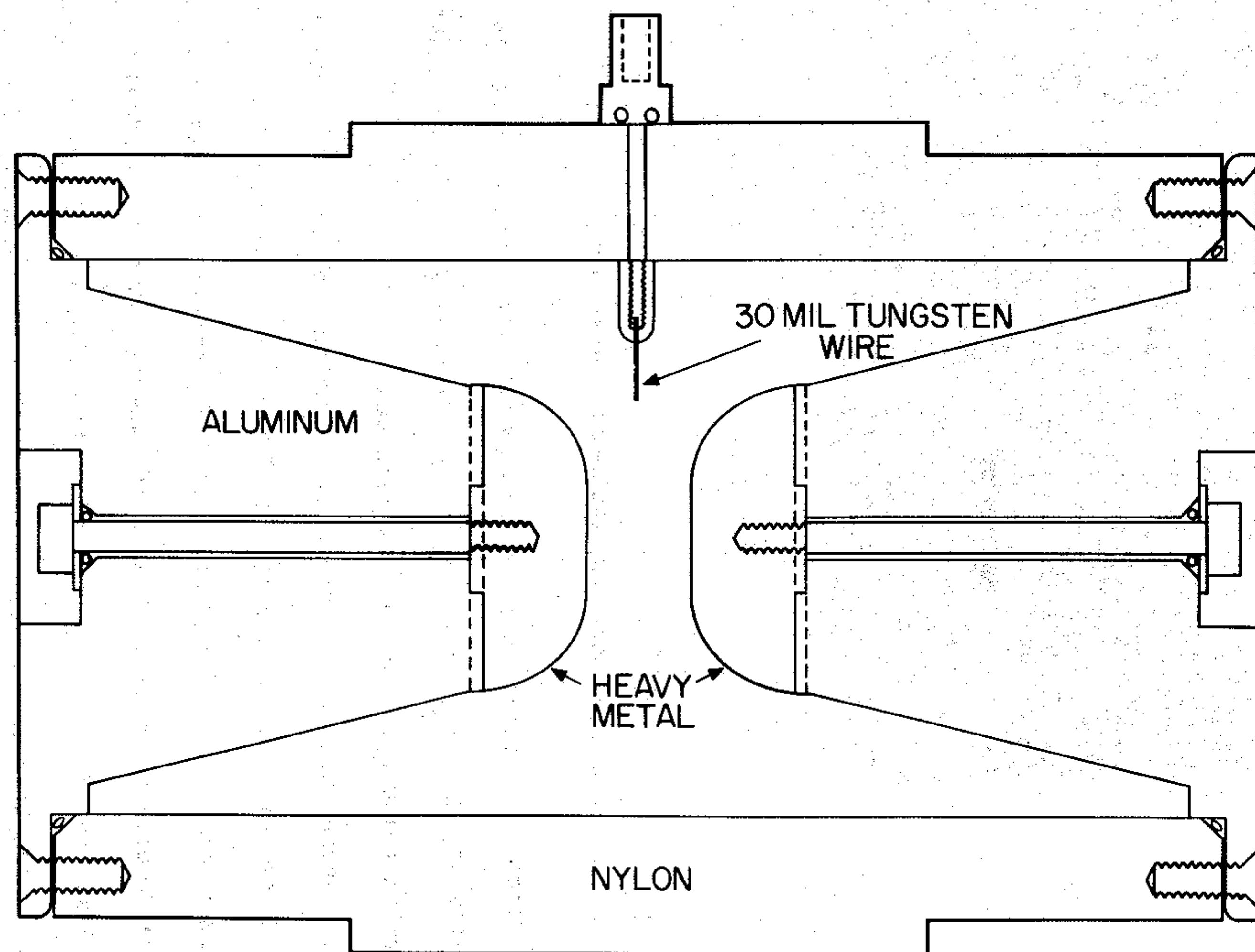


Fig. 7. REBA Triggered Spark Gap

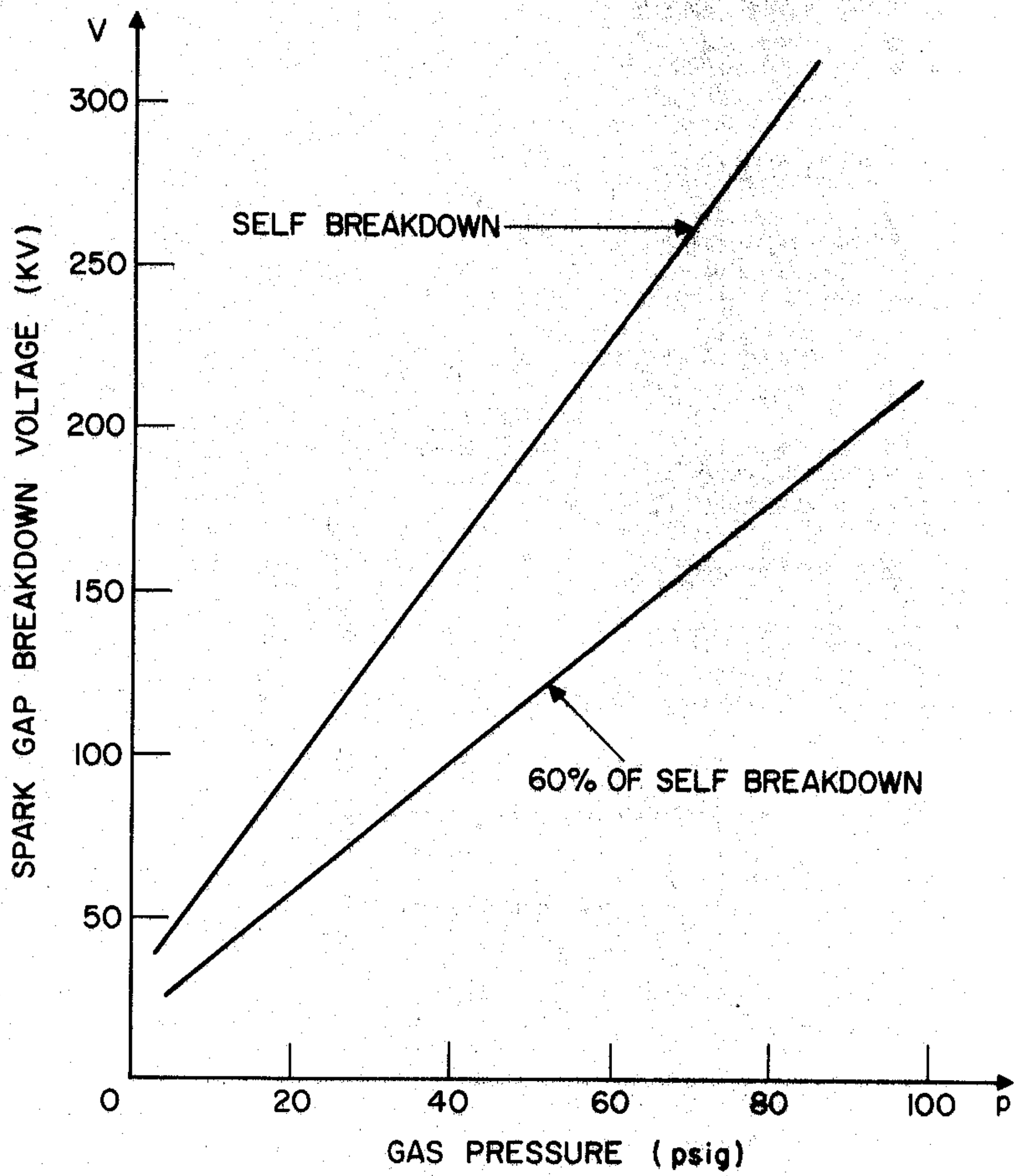


Fig. 8. Spark Gap Breakdown Curve

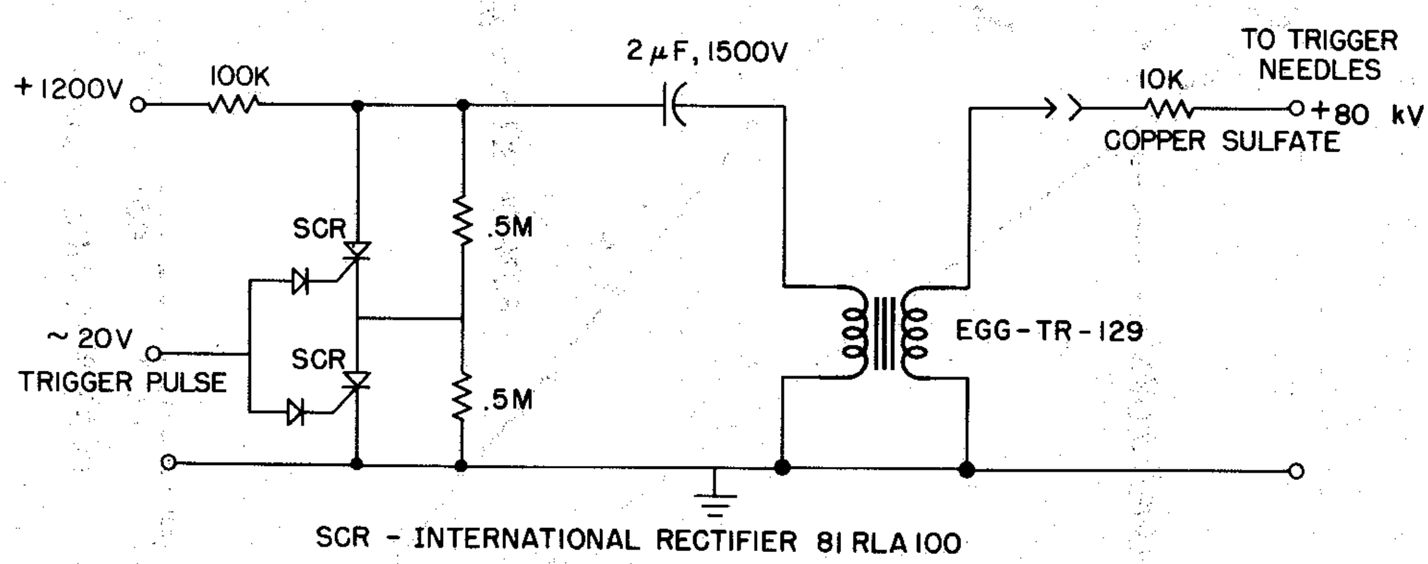


Fig. 9. Spark Gap Trigger Circuit

Blumlein Transmission Line

Fig. 10 is a side view of one of the two Blumlein transmission lines. The impedances and capacities are 7.5 Ω, 4.9 nF for the outer line and 10.1 Ω, 3.15 nF for the inner line. The transmission line will generate a 73 nsec pulse across the output tube. The return line corresponds to L_2 in Fig. 4 and is 3.2 μH.

The Blumlein switch initiates the voltage transient in the Blumleins and affects the risetime of the voltage pulse across the output tube. Using formulas developed by J. C. Martin, AWRE.[5] the switch risetime can be determined.

$$\tau_R = \frac{5}{Z^{1/3} E^{4/3}}$$

$$\tau_L = \frac{L}{Z}$$

τ_R = risetime due to the resistive phase of the breakdown (nsec)

τ_L = risetime due to the inductive phase of the breakdown (nsec)

E = electric field strength in the switch (0.36 MV/cm)

Z = impedance of the inner transmission line (10.1 Ω)

L = inductance of the spark channel (150 nH)

$\tau_R \approx 10$ nsec

$\tau_L \approx 15$ nsec

$\tau_{TOTAL} = \tau_R + \tau_L = 25$ nsec.

This time constant together with the time constant associated with the output tube determines the risetime of the output voltage pulse.

A computer program developed by J. E. Boers[6] was used to analyze the voltage gradients in the Blumleins. Fig. 11 is an equipotential plot of the switch end of the inner transmission line. The electric field near enhancement points was kept below 0.65 MV/in; the breakdown level for the type of oil used in REBA is 0.91 MV/in for 1 μsec pulses.

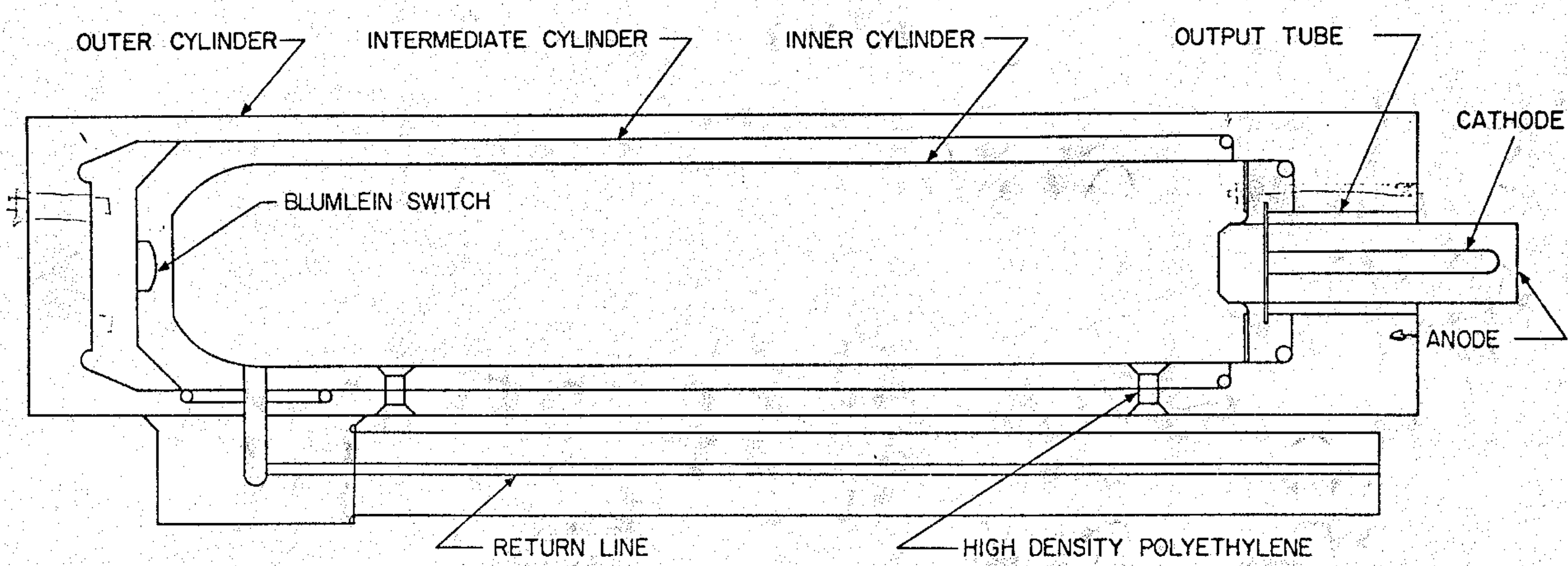


Fig. 10. Cross Section of REBA Blumlein

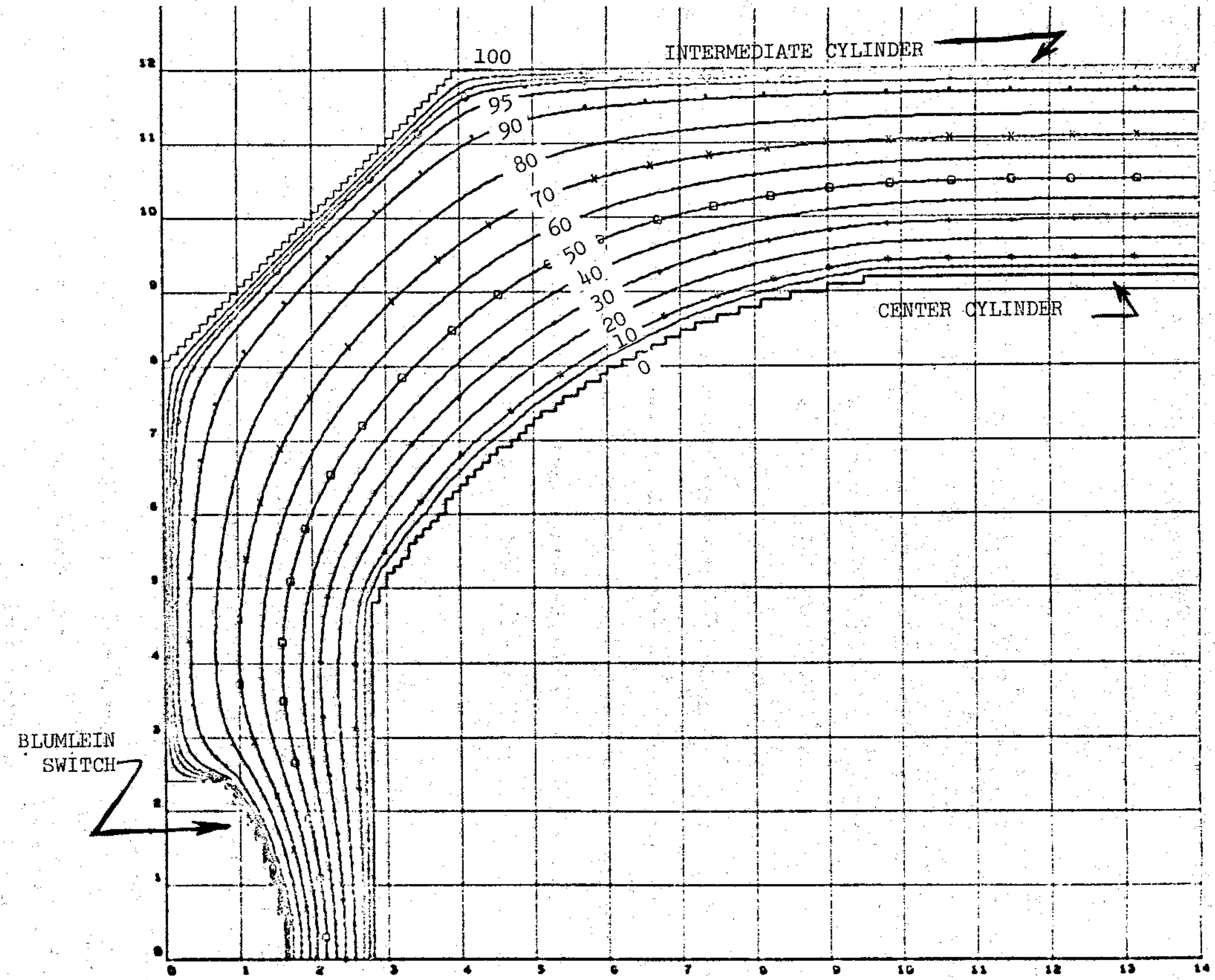


Figure 11. Electric Field Plot of the Blumlein Switch Region (numbers shown are percentage of applied voltage between intermediate and center cylinders)

High density polyethylene truncated cones are used to support the Blumleins. High density polyethylene is used because of its high pulsed breakdown voltage and mechanical strength, and its dielectric strength is similar to that of the insulating oil.

Output Tube

The tube used in REBA is shown in Fig. 12. The tube envelope consists of eighteen lucite insulators, 24 inches in diameter, alternated with aluminum grading rings.[7] Each lucite insulator is 1.75 inches thick and the aluminum grading rings are 0.25 inches thick. The grading rings provide a more uniform voltage gradient across the insulator surfaces and capacitively grade the pulsed voltage. At pressures with the tube of typically 10^{-5} Torr, the insulator rings can withstand an electric field of 180 kV/in before surface breakdown occurs. For a 4 MV pulse on the tube, the stress on the insulators is 127 kV/in. This reduced level should extend the life of the tube and increase the maintenance intervals.

The cathode shank and hemispherical cathode tip are made of 303 stainless steel. The anodes are 4 mil thick titanium foil. The cathode-anode separation is typically 2-3/4 inches.

Drift Chamber

Electrons, after leaving the output tube, enter the drift chamber. By varying the background gas pressure within the drift chamber, the electron trajectories can be modified[8] to tailor the fluence to meet specific applications.

Monitors

The voltage and current monitoring on REBA include a voltage monitor across each of the output tubes, a voltage monitor in the Marx generator, and a current monitor in each of the output tubes.

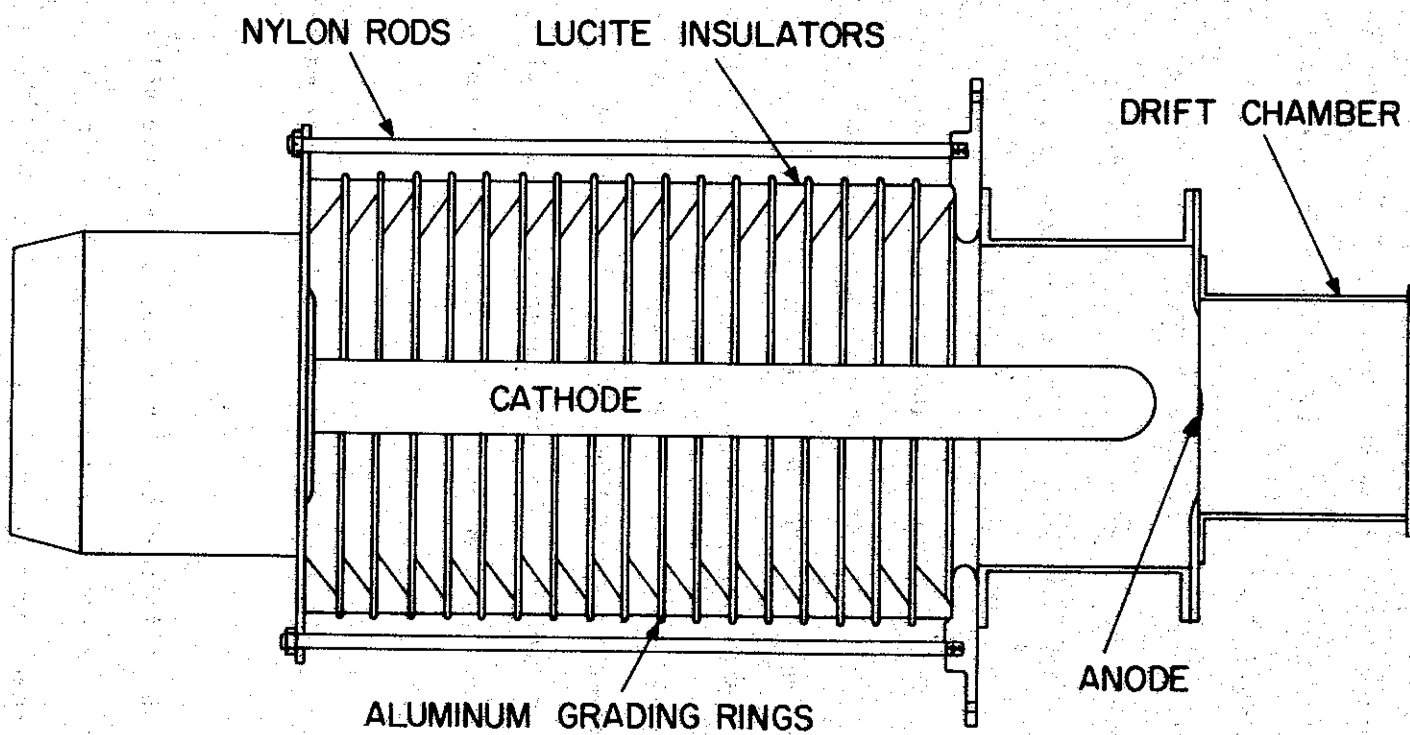


Fig. 12. REBA Tube

The voltage monitors are resistive voltage dividers constructed of polyvinyl chloride tubing filled with a copper sulfate solution. Fig. 13 is a sketch of the voltage monitor used. The same solution of copper sulfate is used between all electrodes to insure that the attenuation factor will remain constant with any changes in conductivity of the solution. Care is taken not to load the pickoff section with carbon resistors.

The resistive dividers are calibrated by discharging a capacitor charged to a known voltage(5 to 10 kV) through the divider and measuring the voltage across the pickoff section of the divider. The measured attenuation factor of the dividers is, within experimental errors, equal to the attenuation factor calculated from the geometry of the divider. The estimated accuracy of voltage measurements on REBA, including the errors in the oscilloscopes used to record the signals and the external attenuators, is within ± 15 percent.

Fig. 14 is a photograph of the current monitor used on REBA. The monitor consists of 400 one-ohm, 1/2-watt carbon resistors in parallel. The anode plate is separated from ground potential by the parallel resistance, and the voltage on the anode plate is measured by a fast oscilloscope. Calibration of the current monitor was obtained with a sensitive bridge circuit. The estimated accuracy in current measurements is ± 10 percent.

Operating Characteristics and Parameters

Marx Generator

Fig. 15 is an oscillograph of the Blumlein charge voltage under normal conditions. The voltage rises rapidly until the oil gap in the hydraulic Marx switch breaks down and then continues to rise until the Blumlein switch breaks down. Fig. 16 is an oscillograph of the Blumlein charge voltage in the case where the Blumlein switch did not break down on the first charging cycle.

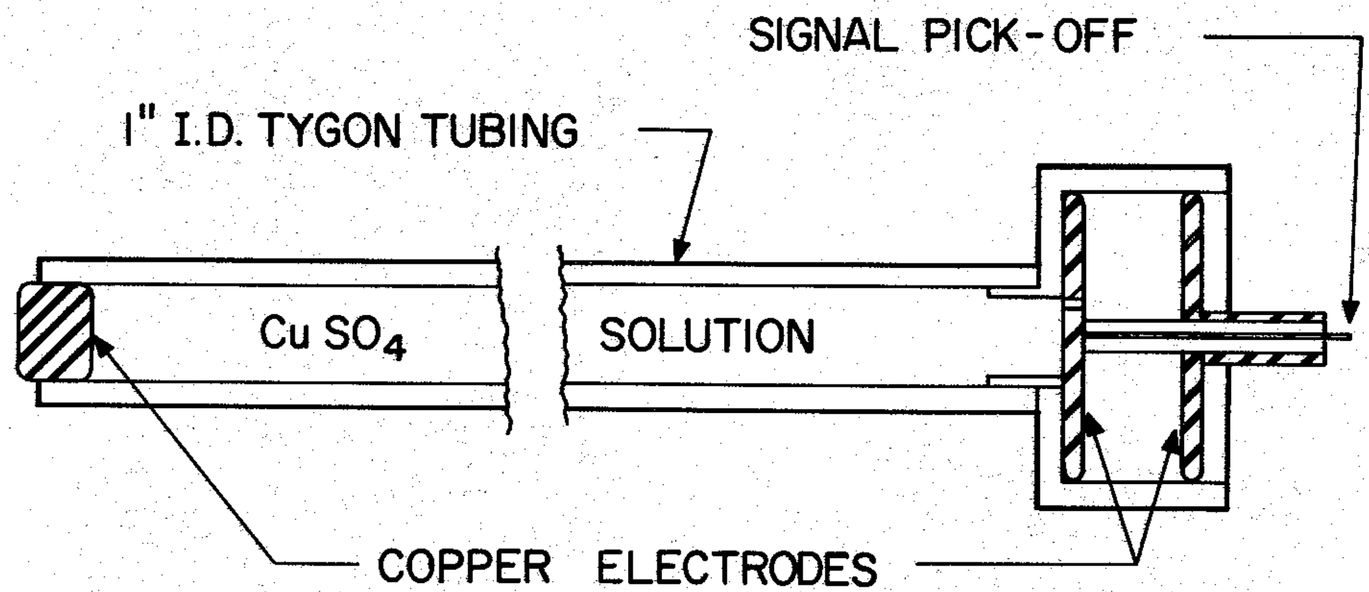


Fig. 13. Resistive Voltage Monitor

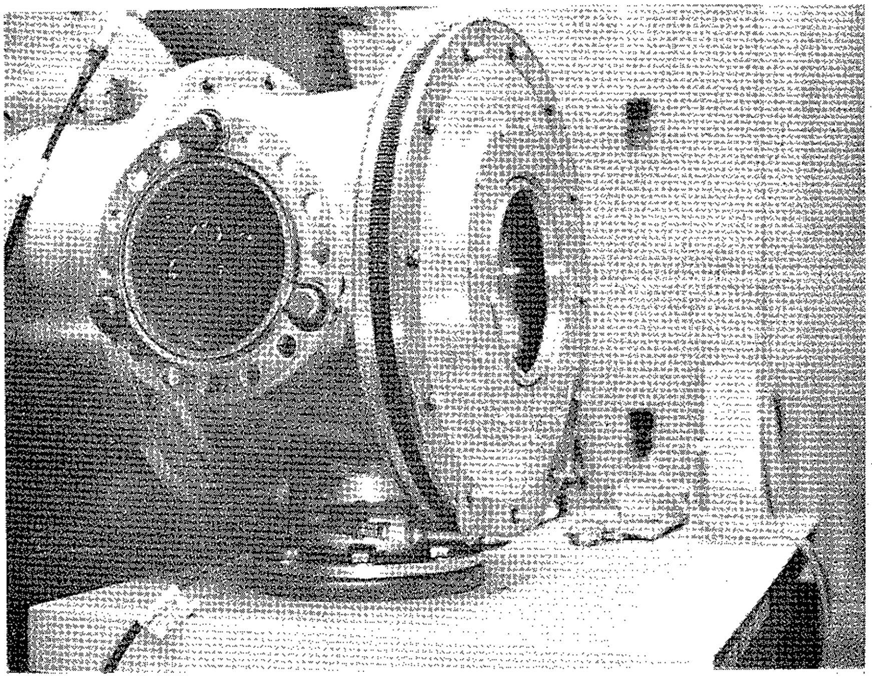


Fig. 14. Tube Current Monitor

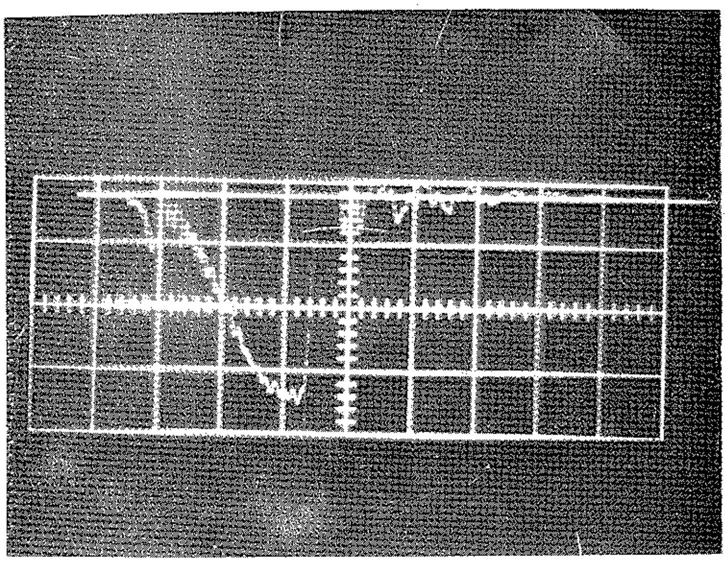


Fig. 15. Blumlein Charging Voltage (normal)
Sweep - 0.5 μsec/div.; Vertical - 0.7 MV/div.

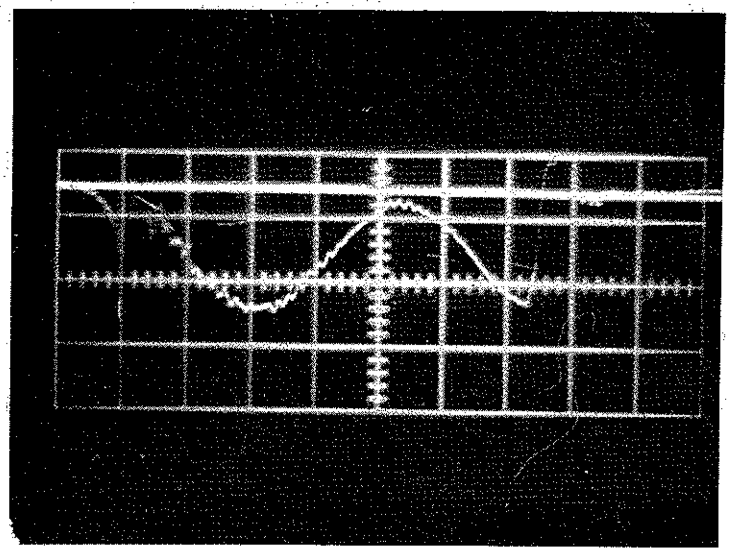


Fig. 16. Blumlein Charging Voltage (ring over)
Sweep - 0.5 μsec/div.; Vertical - 0.7 MV/div.

Using a computer analysis program (Sceptre) to analyze the circuit shown in Fig. 4, the following set of circuit parameters will give the wave form shown in Fig. 16:

$R_S = 3\ \Omega$	$C_1 = 3.15$ nF
$C_M = 12.1$ nF	$C_2 = 4.9$ nF
$L_1 = 1.8\ \mu H$	$L_2 = 3.2\ \mu H$
$R_P = 1000\ \Omega$	$L_M = 24\ \mu H$

A correction to the Blumlein charge voltage is necessary due to the monitor measuring the voltage across the inductor (L_1, Fig. 4) in series with the Blumlein capacitance. The correction amounts to an increase in the measured voltage of 3 to 4 percent.

A capacitive voltage gain due to unequal capacities in the Marx generator and Blumlein exists and was determined from the computer program to 1.13.

Delay and jitter in the machine running time were measured by triggering a 556 oscilloscope with the trigger to the circuit of Fig. 9 and observing the output of PIN detector placed in the radiation field of the machine. The delay measured was 5.2 μsec with a standard deviation $\sigma \approx 100$ nsec for a charge voltage of 70 kV and a gas pressure of 60 psig on the spark gaps. For a charge voltage of 70 kV and a gas pressure of 70 psi, the delay varied from 6 μsec to 18 μsec. This increase in running time is due to increased jitter in the breakdown of the first few spark gaps in the Marx generator.

Tube

Oscillographs of the tube voltage and current pulses are shown in Figs. 17 and 18, respectively. The tube impedance for this shot, using a 3 inch diameter cathode and a 2-3/4 inch anode-cathode spacing, was 84 Ω. The general practice is to define the tube impedance as the peak tube voltage divided by the peak tube current.

A more accurate determination of tube impedance would be to take into account the effect due to the tube inductance;

$$Z_{A-K} = \frac{V_T - L\frac{dI}{dt}}{I}$$

where Z_{A-K} = anode-cathode impedance

I = tube current

V_T = total tube voltage

L = tube inductance

The measured tube inductance for a 3 inch diameter cathode shank, obtained by operating the machine with the anode and cathode shorted, was 0.82 μH as compared with the calculated value of 0.77 μH.

Using Sceptre to analyze the circuit shown in Fig. 19, the calculated curve shown in Fig. 20 was obtained. The gap impedance was assumed to obey Child's law for space charge-limited diodes. The measured points in Fig. 20 were obtained from data taken on Hermes I.

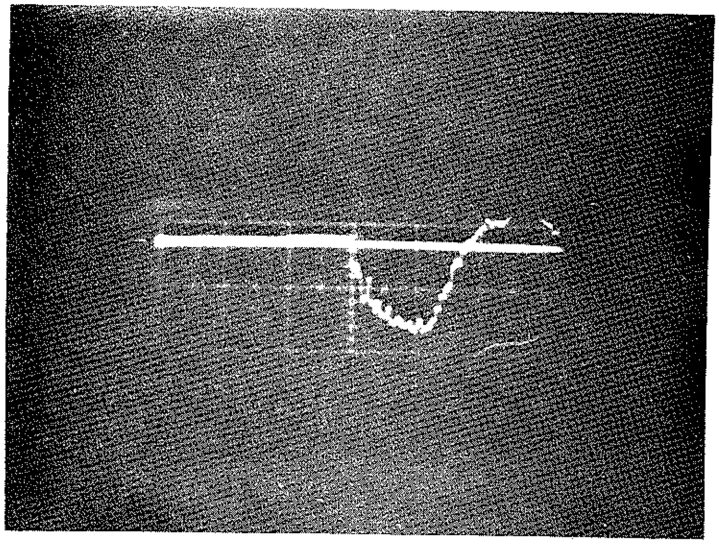


Fig. 17. REBA Tube Voltage
Sweep - 53 nsec/div.; Vertical - 2.72 MV/div.

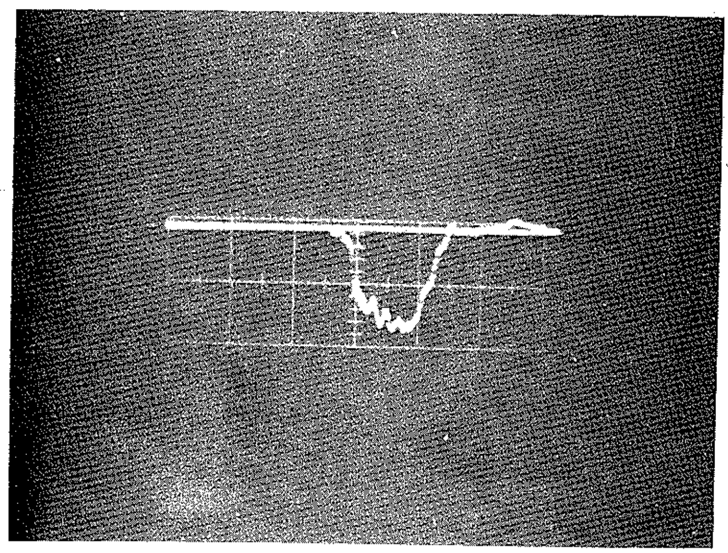


Fig. 18. REBA Tube Current
Sweep - 55 nsec/div.; Vertical - 27.3 kA/di.

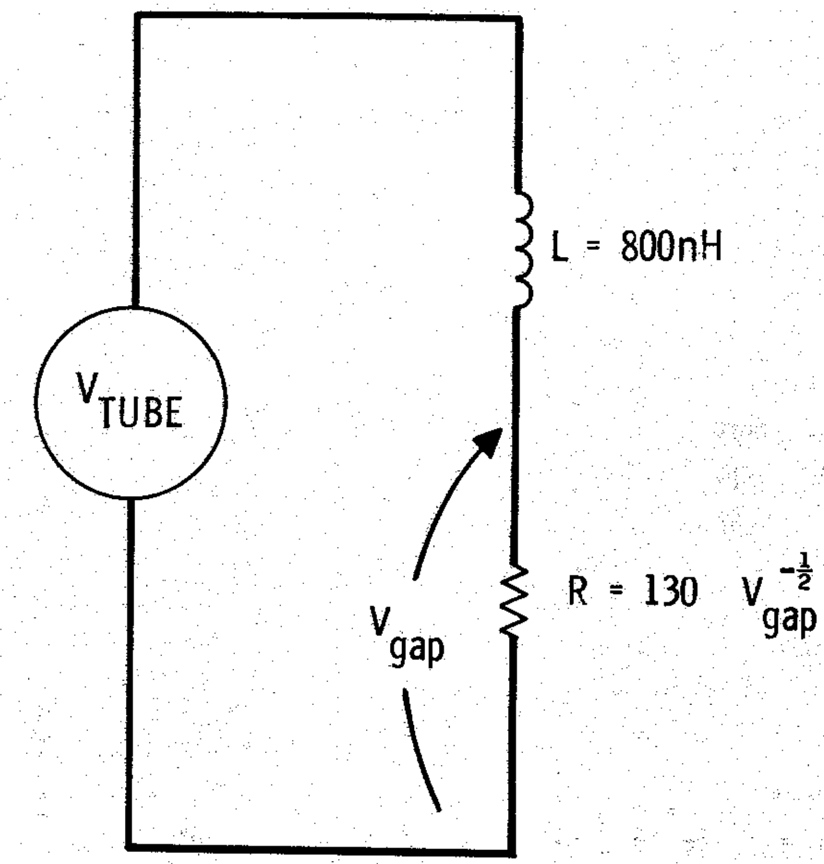


Fig. 19. Circuit Used to Model REBA Tube

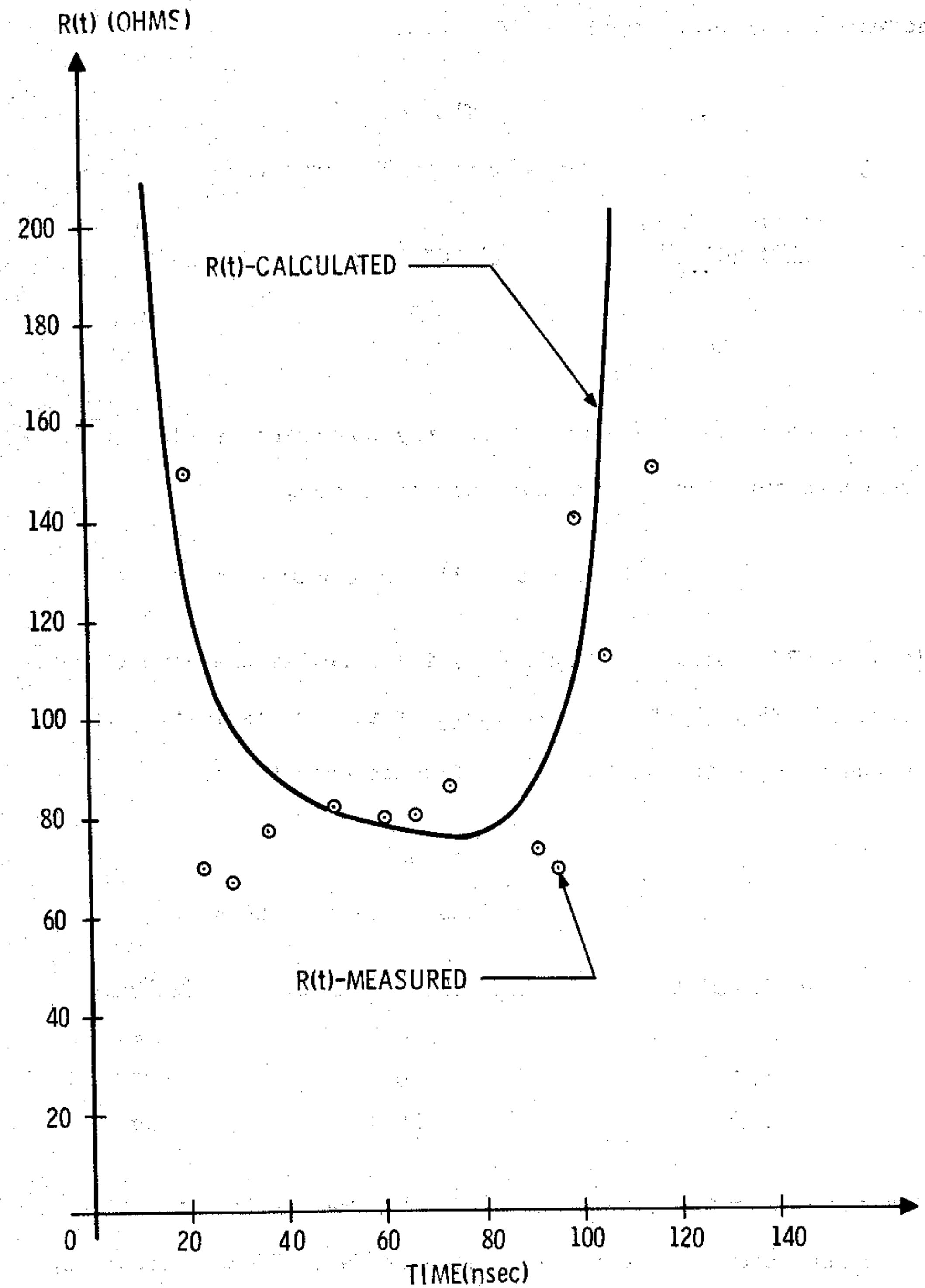


Fig. 20. Diode Resistance Versus Time

Table I gives a listing of typical operating levels for REBA. Repeatability for the values listed is within ± 10 percent.

Table I

REBA Operating Parameters

Cathode Diameter	Blumlein Charge Voltage (MV)	Tube Voltage (MV)	Tube Current (kA)	Tube Impedance (Ω)
3 inches	2.03	3.5	41	86
4 inches	2.00	2.5	44	56

These values should not be taken as the only operating levels available; the machine operators can change the voltage and current levels.

Preliminary Electron Beam Data

Division 5226 (Sandia Laboratories) is currently characterizing the electron beam output of REBA. Table II lists <u>some</u> of the available fluences and effective areas in addition to the uniformity of fluence over the areas.

Table II

Fluences Obtainable from REBA

Area (cm^2)	Fluence (cal/cm^2)	Uniformity
2	200	---
20	30	25%
100	15	50%

Generally the higher the fluence desired, the smaller the effective area becomes for a given uniformity. The values listed in Table II are meant only as an indication of what can be obtained. For specific applications, the Beam Source Applications Division of Sandia Laboratories should be consulted by the experimenter.

APPENDIX

General Physical and Electrical Characteristics of REBA

General Physical and Electrical Characteristics of REBA

General Physical Characteristics

Total Length	- 28 ft
Width	- 24 ft
Height	- 12 ft
Tube Diameter	- 2 ft
Tube Length	- 3 ft
Oil Capacity	- 25,000 gal

Marx Generator

Capacitance per Stage	- 1/2 μF
Number of Stages	- 38
Number of Spark Gaps	- 19
Charging Voltage	- ± 100 kV
Total Energy Stored	- 95 kJ
Output Capacity	- 13,100 pF
Inductance	- 26 μH
Series Resistance	- 3 Ω
Parallel Resistance	- 1,000 Ω
Marx Lossless Output Voltage	- 3.8 MV

Blumlein Transmission Line

Capacitance:	
C_{inner}	- 3,150 pF
C_{outer}	- 4,900 pF
C_{total}	- 8,050 pF
Charging Gain:	
Without Losses	- 1.24
With Losses	- 1.13
Inner Coax Impedance	- 10.1 Ω
Outer Coax Impedance	- 7.5 Ω

Blumlein Transmission Line (cont'd)

Effective Output Impedance	- 17.6 Ω
Blumlein Switch:	
Gap Spacing	- 0 to 4 in
Switch Risetimes --	
$\tau_R = 10$ ns, $\tau_L = 15$ ns	$\tau_{TOTAL} = 25$ nsec
Blumlein Electrical Length	- 73 nsec
Outside Coax Diameter	- 72 in
Middle Coax Diameter	- 59.75 in OD, 59 in ID
Inner Coax Diameter	- 46 in
Oil Stress Levels (2 MV):	
Outside of Intermediate	- .37 MV/in
Cylinder	- .35 MV/in

Output Tube

Number of Insulators	- 18
Stress/Insulator @ 4 MV Tube Voltage	- 127 kV/in
Tube Inductance (3 in diam Cathode Shank)	- 800 nH

References

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