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Two large electron beam generators, Gamble I and Gamble II, have been designed and constructed at NRL. They are used for studies of the propagation of intense pulsed relativistic electron beams and the interactions of such beams with matter. Typical parameters of the electron beams produced are: beam energy - 1 MeV, beam current - 1 MA, pulse duration - 40 nsec. Gamble I is designed to produce beams of up to 20 kJ of kinetic energy; and Gamble II up to 60 kJ. The propagation of very high current relativistic electron beams $(\nu/\gamma \leqslant 10)$ over distances of 1 m, has been studied as a function of drift tube gas pressure and applied axial magnetic field. Details concerning the design of the facilities, typical operating conditions, diagnostics, and experimental results, will be presented.

INTRODUCTION

The purpose of this paper is to provide a general introduction to the NRL relativistic electron beam program, and to report on some recent results on diode development and beam drifting. The paper is divided into four sections. The first introduces the program and discusses some of its objectives; the second provides a summary of the design and operational features of Gamble I and Gamble II, the two large NRL electron beam generators; and the final two sections contain recent experimental results on high energy diode development and beam drifting experiments.

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The NRL relativistic beam program is only four years old, but related research at NRL existed long before that. For example, there were experimental[1] and theoretical[2] studies of electron beam dynamics, and an active program of high voltage technology in connection with exploding wire research[3]. A major effort to produce and study intense relativistic beams was initiated in 1967 with the construction of a 40 ohm oil Blumlein line and a 7 ohm water Blumlein generator. Some details concerning this phase of the NRL work were presented in the last Conference of this series[4].

The first of the large coaxial water transmission line generators, Gamble I, was designed and built at NRL in 1968[5]. This was followed two years later by the development of an even larger generator, known as Gamble II, which became operational in June, 1970[6,7]. Concurrent with this work, research on electron beam propagation was conducted in collaboration with the Cornell University Laboratory for Plasma Studies[8].

The objectives of the NRL program are to advance the state of the art of high voltage, pulsed power technology, to study the physics of intense relativistic electron beams, and to explore various applications of these beams. Among the applications which we are investigating are studies of the effects of intense energy deposition on materials, the generation of microwave radiation, and the utilization of relativistic electron beams for controlled thermonuclear fusion[9].

THE GAMBLE I AND GAMBLE II ELECTRON BEAM GENERATORS

Gamble I and Gamble II are large relativistic beam generators, each capable of producing well over 10^4 Joules of 1 MeV electrons in a 50 nsec pulse. The two generators were designed using similar concepts, and differ from one another principally in size. Therefore, in this section we will concentrate on the design and behavior of Gamble II, making specific reference to Gamble I only where significant differences exist.

Both generators are charged coaxial transmission lines, designed to produce a 1 MV pulse across a field emission diode for 50 nsec. They both utilize high resistivity water as the dielectric. Water was chosen as the dielectric because it is convenient, inexpensive, and self-healing after a breakdown, but primarily because of its very high dielectric constant (80 as compared to two or three for oil or Mylar). This implies that a very high density of energy storage is possible, and that the physical length of a pulse forming line can be considerably shorter than if one were to use a medium with a lower dielectric constant. The reason that water is not used more extensively as a dielectric is that its breakdown properties are highly time dependent. Even if one uses demineralized high resistivity (say, $\rho > 1\ M\Omega$-cm) water, its practical utility as an energy storage dielectric is limited to systems where voltages are maintained for no more than a fraction of a microsecond. Fortunately, extensive studies of the nature of electrical breakdown in water have been conducted by J. C. Martin and his coworkers at AWRE Aldermaston (England)[10]. Their work has not only shown the nature of breakdown, but has provided empirical formulas relating the breakdown field strengths to the electrode polarity and area, and the time for which the field appears at the electrode surface[11]. These relationships were used extensively in the design of Gamble I and Gamble II.

The overall configuration of the Gamble II generator is shown schematically in Figure 1. To the rear of the coaxial line is the Marx generator, which was designed and built by the Physics International Company. It is composed of 120 stages, each of which consists of a single capacitor of 0.5μF at a rated voltage of 85 kV. The stages are charged in parallel and erected by switching them in series, with every third switch being triggered. The total stored energy in the bank is 228 kJ at full charging voltage, and its output capacitance is 4.1 nF.

The Marx generator erects and charges a coaxial water transfer capacitor section of 7.4 nF to a voltage of up to 6.0 MV. The transfer or intermediate storage section is designed to withstand the high voltages for the relatively long charging time of 1.2 μsec. It is used to reduce the more stringent requirements on rapid Marx discharge time which would be needed if the Marx directly charged the pulse forming section. The intermediate storage section and the remainder of the water line are separated from the oil filled Marx generator tank by a pair of 1" thick polyurethane diaphragms. These must support any pressure differentials between the oil and water sections as well as withstanding large voltages during Marx erection and discharge.

The intermediate storage section is, in turn, discharged into the pulse forming line through an overvoltaged water switch. This gap, as well as a similar one at the output of the pulse forming line, were designed using the water breakdown formulas mentioned above. The electrodes were carefully designed so that breakdown due to streamers from the negative electrode will occur at only a slightly lower voltage level than breakdown due to streamers from the positive electrode. This condition results in a minimum gap spacing and therefore minimum switch inductance. The detailed design of the switch, as well as most other parts of the generator, was carried out making extensive use of electrolytic field plotting tanks and an electrostatic potential plotting computer code[12]. This was done to ensure that the electric fields were kept sufficiently below breakdown values throughout the system.

In order to assure statistical reproducibility, each of the two switches must be adjusted to fire at between 80 and 90% of peak voltage. This imposes a significant loss in energy transfer through the system. For this reason, as well as the need for precise time synchronization of the beam generator for some applications, effort has been devoted to the development of command triggered water switches for use in Gamble II. The preliminary design of a switch being developed to go at the output of the pulse forming line is shown in Figure 2[13]. A positive trigger signal, derived from the intermediate storage output switch causes breakdown to proceed from the disk electrode.

The very high voltages on the intermediate storage and pulse forming sections of Gamble II, make the use of gas switching impractical there. This is because the required gap spacing to prevent breakdown would make the switch so inductive as to significantly degrade the risetime of the generator pulse. On the other hand, at the lower voltages in Gamble I (3 to 4 MV) one can use gas switches. A single channel, command triggered gas switch has been designed and installed by the Ion Physics Corporation at the output of the Gamble I intermediate storage section, and a multichannel gas switch will soon be incorporated at the pulse line output[14].

The energy of the intermediate storage section is switched into the pulse forming section when the voltage on the former reaches ~90% of peak. It is transferred through an inductive extension of the pulse forming line to increase the charging time of the pulse line to 180 nsec. This is done in order to reduce the amplitude of the "prepulse" voltage signal, which appears across the field emission diode before the main pulse, to less than 10% of the main pulse amplitude. The prepulse signal is proportional to the rate at which voltage appears across the output switch and hence can be reduced by slowing the charging of the pulse line.

The pulse forming section is biconical, with the outer conductor diameter tapering from 9' to 3 1/2'. The electrical length of the line is 50 nsec, and its characteristic impedance is 5.8 ohms. The pulse forming line was designed to have this impedance for two reasons, although the final output impedance of the generator is only 1.5 ohms. First, the use of a single channel switch at the pulse line output introduces significant inductance in the circuit. In order to minimize the effect of this inductance on the pulse risetime, it is necessary to keep the impedance as high as possible. The resulting 10% to 90% risetime at the output of the pulse line output on Gamble II is 15 nsec. Second, if one uses the water breakdown data discussed above, one can show that 5.8 ohms is the characteristic impedance of a coaxial water dielectric line designed such that breakdown is equally likely to start from the negative inner conductor or the positive outer one. This then represents the impedance line which can store or transmit the most electrical energy for a given outer diameter, since either higher or lower impedance lines will breakdown at lower fields.

The final generator output impedance is achieved by propagating the pulse line output pulse down a coaxial water section in which the inner conductor tapers outward. This acts as a continuous transformer, reducing the impedance from its value of 5.8 ohms at the input to 1.53 ohms at the output. The output impedance was chosen to maximize the energy delivered to an idealized diode consisting of an inductance of 20 nH in series with a resistance of 0.6 ohms, with the further constraints that the resistive voltage drop be 1.0 MeV and that the energy be delivered in 50 nsec. The length of the tapered transformer section was chosen to limit the energy loss due to droop in the voltage waveform to less than 7%. Details of these calculations as well as others involved in the design of Gamble II, may be found in Reference 6.

The energy pulse travelling down the transformer must be transmitted from the water line to the vacuum region in which the field emission diode is located. This transition region, or diode support structure, is a key element in the generator design since it must be designed for minimum inductance while preventing breakdown. It must also provide a mechanical interface between the water and vacuum regions and be easily cleaned, so that debris from the diode region does not degrade the performance of the insulators in the diode support structure.

The G-4 diode structure[6], which is used on Gamble I and II, is shown schematically in Fig. 3. The acrylic spacers, alternated with aluminum rings, serve to insulate the cathode region from the grounded outer tank, and guide the electromagnetic energy flow toward the diode. The interior sides of the acrylic spacers are angled to decrease the probability of voltage breakdown. The spacers also act as a mechanical interface between the water and the vacuum region of the diode. Great care must be exercised in the design of this region to minimize voltage flashover. For example, metallic falsework is introduced to redistribute the fields and produce a more uniform potential gradient across the insulator surfaces. An electrostatic field plotting code[12] as well as electrolytic tank field plotting, were used extensively in the design work. The G-4 diode structure was designed to hold off 1.5 MV for 70 to 80 nsec and provide an effective inductance of about 30 nH. An advanced diode structure, known as G-5, is presently under development[15]. It will utilize a single 2 1/4 inch thick acrylic insulator plate rather than the acrylic and aluminum spacer ring configuration presently used. This will greatly simplify the task of cleaning the insulator surfaces between shots. It is believed that debris which accumulates on these surfaces and is not removed, is a major source of the voltage flashover which can appreciably shorten the energy pulse delivered to the beam.

The electromagnetic energy finally appears as a voltage pulse across the field emission diode. Although considerable progress has been made[16], there is much that is not yet understood about the dynamic behavior of these diodes at high energies. In particular, we have devoted a good deal of effort toward developing reproducible, constant impedance diodes capable of producing beams of several kJ/cm^2. This work is discussed in the next Section.

Diode current and voltage are monitored with standard magnetic loop probes and capacitive voltage dividers. Typical Gamble II diode current and voltage traces are shown in Fig. 4, as are the calculated power and impedance as functions of time. For beam propagation studies, the anode is typically a sheet of 1/4 mil aluminized Mylar. The drifting beam is typically propagated in a 4" plexiglass drift tube, lined with an aluminum mesh return conductor and filled with air at a pressure of between 0.1 and 5 Torr. The diode itself is maintained at a pressure of $\sim$0.5 mTorr. An external axial magnetic field of up to 10 kG is generally applied over the entire diode and drift tube region. The magnetic field pulse is sufficiently slow that the field can penetrate the entire diode. The configuration of the front end of one of the generators, with the diode and drift tube, is shown schematically in Fig. 5.

In summary, Gamble I and Gamble II are two large coaxial water transmission lines designed to deliver 50 nsec long, 1 MV pulses to field emission diode loads. They both employ Marx generator charging, with water transfer capacitors, coaxial pulse forming lines, and tapered transformer sections. Their detailed electrical characteristics are compared in Table 1.

DIODE DEVELOPMENT

As was mentioned above, a serious obstacle to the efficient utilization of these machines, was the lack of highly reproducible diodes capable of producing beams of several kJ/cm^2. The cathodes previously used on Gamble I and II were stainless steel disks, of four to seven centimeters in diameter, in which a cross hatched pattern was milled. These cathodes were typically used for a number of shots before being replaced. Plasma cathodes, in which the milled out regions were filled with a plastic or epoxy, could not be used because of the very rapid erosion of the fill material at these energies. The results with cross-hatched cathodes showed current and voltage reproducibility to no better than 15 or 20%, and variations in pulse width that were even worse. In addition to shot to shot variation in beam parameters, the diode impedance as a function of time also showed an unacceptably rapid falloff[17].

In order to improve on this situation, a variety of different cathodes and diode preparation techniques were explored. The one which has, to date, shown the most promise utilizes a cylindrical disk cathode. The disk face is turned flat and a spiral groove some 4 mils deep is cut with a spacing of about 10 mils between grooves. The surface is then coated with 1000Å of aluminum. This leaves a fresh surface with approximately triangular depressions separated by flat regions. A cathode is shown in Fig. 6. What is apparently as important a consideration as the disk geometry, is a microscopic investigation of the surface which shows whisker densities of 10^5 to 10^6 cm^{-2} on fresh cathodes. After a shot in which the diode impedance has fallen very rapidly to a low value, large members of these whisker sites show evidence of local explosions, as has been reported[18] in other studies. Such evidence of whisker explosion is lacking in normal shots. In either event, it has been found necessary to replace the cathode after each shot to obtain maximum reproducibility.

If the cathode is constructed as described above, and if the surface is refinished after each shot, reproducibilities in current and voltage waveform of better than $\pm$ 5% can be achieved, when external magnetic fields are employed. Moreover, this scatter is probably as much due to lack of reproducibility in the generator output waveform as in the diode behavior. Further, the time-varying impedance now shows a fairly gradual decrease, as shown in Fig. 7. One of the problems which remains with these cathodes is the very nonlinear variation of impedance with cathode-anode gap spacing. At relatively large spacings the variation follows Child-Langmuir scaling but as one decreases the spacing a point is reached beyond which the impedance falls very sharply. For example, with a 33 cm^2 cathode, a decrease in spacing from 0.85 cm to 0.80 cm carries the beam from a $\sim$ 2 ohm level to a few tenths of an ohm. It is felt that this is a field effect, since the same result can be produced by increasing the driving voltage on the diode by a relatively small amount.

We are continuing to study the parametric behavior of these diodes in order to elucidate the physical phenomena that determine their behavior. Our preliminary hypothesis is that, while the prepulse voltage is on the diode, only a small fraction of the whisker sites are field emitting and the total current is quite low. When the main voltage pulse arrives, the applied electric field and the locally enhanced fields at the whiskers can increase by an order of magnitude, causing many more whisker sites to emit, giving relatively uniform emission over the whole cathode. Some heating and explosions of these sites enhance the emission. Moreover, release of adsorbed gases and local explosions may form a plasma sheath near the cathode surface. This permits currents well in excess of the Child-Langmuir value to flow. Whether it is motion of this cathode sheath or material from the anode surface that causes the time variation of the impedance, is not yet clear. We have found, empirically, that the amount of gas adsorbed or absorbed on the anode surface can play a very important role in determining the impedance characteristics of these diodes. On the other hand, the transition to a "low-impedance mode" described above most likely starts with whisker explosions on the cathode, and the subsequent jetting of material across to the anode.

Summarizing, there is clearly still much about the behavior of these diodes that is poorly understood. However, semiempirical studies have permitted the development of low impedance diodes capable of reproducibly producing beams of more than 30 kJ at current densities of 20 to 40 kA/cm^2. The electron beams that have been produced in these experiments have had peak currents well in excess of 1 MA, with electron energies of the order of 1 MeV.

BEAM PROPAGATION STUDIES

Preliminary experiments have been performed on the propagation of intense relativistic electron beams from the Gamble I generator in applied magnetic guide fields[19]. Nominally 600 kV and 300 kA (peak) beams of 40 nsec duration (fwhm), were injected through a 1/4 mil aluminized mylar anode foil into a drift tube containing air at 200 to 400 mTorr pressure. The anode and cathode structures, as well as the 4 1/2" ID lucite drift tube were placed within a 120 cm long 6" I.D. solenoid. The drift tube was lined with wire screen to provide a return conductor for the beam. The solenoid was pulsed using a 640 μF capacitor bank, with the resulting risetime of the magnetic field in the coil being about 8 msec. All metal structures within the field, including the stainless steel cross-hatched cathode, were fully permeated by the field. The magnitude of the applied field has been varied from 0 to 10 kG. Diagnostics consisted of radiation dosimetry, carbon block calorimetry, pin hole radiography, and the use of magnetic pick up loops within the drift tube. The efficiency of beam energy propagation was monitored in two ways. Absolute measurements of propagated energy were made using a carbon block calorimeter placed at various distances down the tube. To check this, relative radiation dosimetry measurements were made by placing a thin tantalum foil in the beam path and monitoring the resulting radiation with thermoluminescent dosimeters (TLD's). The TLD measurements were compared with similar measurements made at the injection anode foil thereby giving direct information on the efficiency of energy propagation.

The basic result of this work is that an unexpectedly small guide field is sufficient to efficiently transport the beam, as is shown in Fig. 8. Shots which were significantly different from the nominal values mentioned above, were suitably normalized. The average T.L.D. energy observed with the tantalum foil at the anode, including shots which required normalization, is represented by the dashed line, with the range shown at the right. The 85% line has been drawn in, as that is the efficiency observed in earlier work at Cornell University on $(\frac{\nu}{\gamma}) = 2.5$ beams (although that was observed at 2.5 m)[20]. As can be seen in Fig. 8, our data are consistent with that level, although our beams had $(\frac{\nu}{\gamma}) = 7$ and considerably larger total beam energies (of the order of 5 kJ, as compared with 1 kJ or less).

It is quite interesting that 2 to 3 kG is enough for efficient transport of our $\frac{\nu}{\gamma} = 10$ beams. This is to be compared with the 1.6 kG required at Cornell for $\frac{\nu}{\gamma} = 2.5$ beams[20]. This implies that the minimum required value of field varies more slowly than the linear dependence on (ν/γ) that might have been expected. The explanation for this low value appears to be related to a balance of perpendicular particle pressure in the drifting beam with magnetic pressure. A simple particle model of beam electrons spiralling down field lines leads to the relationship[21]:

$$\frac{B_o^2}{2\mu_o} = nW_\perp$$

where B_o is the applied axial field, n is the beam electron density, and $W_\perp$ is the component of beam electron kinetic energy due to transverse motion. This is the perpendicular pressure balance equation for the electron beam in the guide field. For a 300 kA beam, and a 20 cm^2 cathode, $n = 3 \times 10^{12}/cm^3$; at 2 kG, we would be allowed perpendicular energy per particle, $W_\perp$, of only 80 keV, which is most likely an underestimate, given what we know of beam pinching in the cathode-anode gap.

The above calculation is overly pessimistic for several reasons. First, since the cathode is 5 cm in diameter and the drift tube is 10 cm, there is considerable room for beam expansion before hitting the walls. There is, indeed, evidence of just such beam expansion to achieve pressure balance. If the effective beam area were to double, the allowed perpendicular energy per particle would be 160 keV, or more than 25% of the total kinetic energy. Second, in relatively small, high ν/γ beams such as we have here, a large fraction of the perpendicular energy can be introduced by pinching within the diode itself. However, if one applies an axial guide field to the cathode-anode gap, experiments have shown[22] that complete control of the diode pinch can be obtained if

$$\frac{B_o}{B_s} > \frac{\gamma}{\nu}\ \frac{r}{2d},$$

where B_s is the maximum self field of the beam, r is the cathode radius, and d is the gap spacing. In the present set of experiments, the required applied field is about 5 kG, but between zero and this field, there is a gradual variation between total pinch and total control of pinch. Thus, as the external magnetic field is increased, not only is the confining magnetic pressure increased, but the perpendicular beam pressure due to diode pinching is decreased. This, together with actual expansion of the beam in the drift tube, appear to be sufficient to explain the observed propagation.

Two points relevant to this argument are illustrated in Fig. 9. It shows the damage done to the tantalum foils placed at 1.05 meters from the diode at four different values of magnetic field. First, we can note that the lower the field value, the more diffuse is the boundary of damage on the tantalum. In fact, at the highest field value, 7.4 kG, this boundary is very narrow. Secondly, it is clear that the highest field shot has the smallest damage area. Both of these are completely verified in the pin-hole radiographs.

Also seen in Fig. 9 is evidence of a flute instability on the beam as seen by the damage patterns on the foils from the higher magnetic field shots. This is observed on the tantalum foils and the pinhole radiographs on every shot above about 4 kG, although neither the exact pattern nor the number of lobes is reproducible. Figure 10 shows a series of three shots, one with the tantalum converter at the anode, one with it 1/2 meter from the anode and one with it at the usual position (1 meter from the anode). Assuming the linear regime of this instability extends at least as far as the 1 meter point, these foils seem to indicate an e-fold length for flute amplitude of about 1/2 meter. For a beam velocity of 2×10^8 m/sec, this implies an e-folding time of two or three nanoseconds. A second observation from Fig. 10 is that the higher azimuthal modes (of order 14) seem to dominate at the 1/2 meter point, while lower mode numbers (of order 6 or 8) dominate at the 1 meter point.

If one calculates the flute instability growth time, assuming a sharp beam boundary separating the beam and its self-generated plasma from the neutral gas, one obtains[23]:

$$t = L\sqrt{\frac{M}{Np_\perp}}$$

where N is the mode number, L is the characteristic length of the magnetic field inhomogeneity, M is the total mass density of the plasma, $p_\perp$ is the perpendicular plasma pressure, and t is the growth time. We assume a field inhomogeneity of 20% occurring over a length scale of 30 cm, based on the nature of the magnet coils we have used. We also assume the pressure is predominantly that of the beam transverse kinetic motion, taken to be 200 keV. It is somewhat harder to estimate the mass density. There is much evidence that background ionization in a drift region builds up relatively slowly until the large induced electric fields due to the rising magnetic field of the beam front can cause avalanche breakdown[24]. Once breakdown occurs, the plasma mass density is much too high for this instability to grow on the time scale of our experiments. However, before avalanche breakdown occurs, in the first nanosecond or two after the beam front passes a point in the drift tube, the plasma density is mainly beam electrons and the few ions which are present. For ion number densities small compared to the beam density ($n_i < 10^{-2}\, n_b$), the growth time can easily be of the order of 10 nsec divided by the square root of the aximuthal mode number. It is also consistent with the higher order modes dominating at shorter distances. These modes tend to grow first, but will saturate when their amplitude becomes comparable with wavelength. The lower modes will thus eventually dominate as is observed.

Summarizing, we suggest that the fluting instability occurs very early in time and, as soon as the background plasma builds up and avalanche breakdown occurs along the path taken by the beam front, the flutes are frozen in by the plasma mass. The result is a very clean flute pattern, with sharp boundaries surrounding a relatively uniform beam.

CONCLUSIONS

We have described the design parameters and operating conditions of two large electron beam generators, Gamble I and Gamble II. These machines are capable of producing 20 and 60 kJ of 1 MeV electrons, respectively, in pulses of 50 nsec or less. They are being used for fundamental beam studies and applications. We have described some recent developments in field emission diode design, which permit good reproducibility and impedance characteristics even at high beam energies. We also have discussed recent work on beam propagation in axial magnetic fields done with Gamble I.

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10. Much of the original data concerning dielectric breakdown, as well as a variety of other information concerning the design, construction and operation of pulsed power generators, was developed by J. C. Martin and his coworkers at A.W.R.E., Aldermaston, England.

11. Based on experimental data obtained by J. C. Martin and coworkers, we can derive expressions for breakdown due to streamers from the positive electrode of a water dielectric system:

$$F_{(+)} t^{\frac{1}{3}} = 0.287A^{-.0902}, \text{ and}$$

for breakdown due to streamers from the negative electrode:

$$\frac{F_{(-)} t^{\frac{1}{3}}}{\alpha} = 0.579A^{-.0920}$$

where $F_{(+,\,-)}$ is the electric field in MV/cm on the surface of the electrode corresponding to breakdown due to streamers from the (positive, negative) electrode; t is the effective time in microseconds and is defined as the time that the surface field exceeds 63% of the breakdown value; A is the effective area in cm^2 and is defined as the area over which the electric field > 90% of the breakdown field; and $\alpha \equiv 1 + 0.12 \left(\frac{F_{max}}{F_{mean}} - 1\right)^{\frac{1}{2}}$.

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21. Suppose we assume that all beam electrons are spiralling down the drift tube along magnetic field lines with the same velocity, $v_\perp$, perpendicular to the applied field. Then all the beam electrons will have Larmor radii, R_L, given by (MKS units)

$$R_L = \frac{v_\perp \gamma m}{eB_o} \quad ,$$

where B_o is the magnitude of the applied field and γ is the usual relativistic factor. If the beam is uniform out to a sharp boundary, there is a net motion of electrons around the beam only near the boundary. This looks like a single turn solenoid, which results in a diamagnetic field, B_d , given approximately by

$$B_d = \mu_o n e v_\perp R_L = \mu_o \frac{n v_\perp^2 \gamma m}{B_o}$$

where n is the beam electron number density. Beam electrons would no longer be confined at the boundary, however, when B_d exceeds B_o. To find the limit, take these two fields equal, and the result is

$$\frac{B_o^2}{2\mu_o} = \frac{n\gamma m v_\perp^2}{2} = nW_\perp$$

where $W_\perp$ is the perpendicular kinetic energy of an electron.

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FIGURE CAPTIONS

Fig. 1. - The Gamble II generator, showing: (1) Marx generator; (2) polyurethane diaphragm separating oil and water sections; (3) water transfer capacitor; (4) pulse forming line; (5) tapered transformer section; (6) field emission diode.

Fig. 2. - Triggered water switch for the pulse forming line of Gamble II.

Fig. 3. - The G-4 diode envelope employed on Gamble I and II, showing: (1) field emission cathode; (2) inner (cathode) conductor; (3) outer (ground) conductor; (4) acrylic spacer rings; (5) aluminum rings; (6) metallic falsework to guide energy flow; (7) vacuum region; (8) water region.

Fig. 4. - Measured diode beam behavior on Gamble II. The cathode was 4 cm in diameter; the diode gap was 6.5 mm; the background pressure was 2×10^{-4}Torr; and the applied axial magnetic field was 8 kG. Total beam energy was 28 kJ.

Fig. 5. - The front end of a relativistic electron beam generator, showing the field emission diode, drift tube, and magnetic guide field coils.

Fig. 6. - A new cathode of the spiral-grooved variety.

Fig. 7. - Impedance variation using the spiral-grooved cathode. Shots #1 and #2 are 25 kJ beams; shot #3 is an 18 kJ beam with a carbon anode.

Fig. 8. - Beam propagation efficiency as a function of applied magnetic field at one meter down the drift tube.

Fig. 9. - Tantalum foil damage as a function of magnetic field at one meter down the drift tube.

Fig. 10. - Tantalum foil damage as a function of distance down the drift tube, at $B_Z = 5.4$ kG.

Table 1. - Electrical parameters of the Gamble generators.

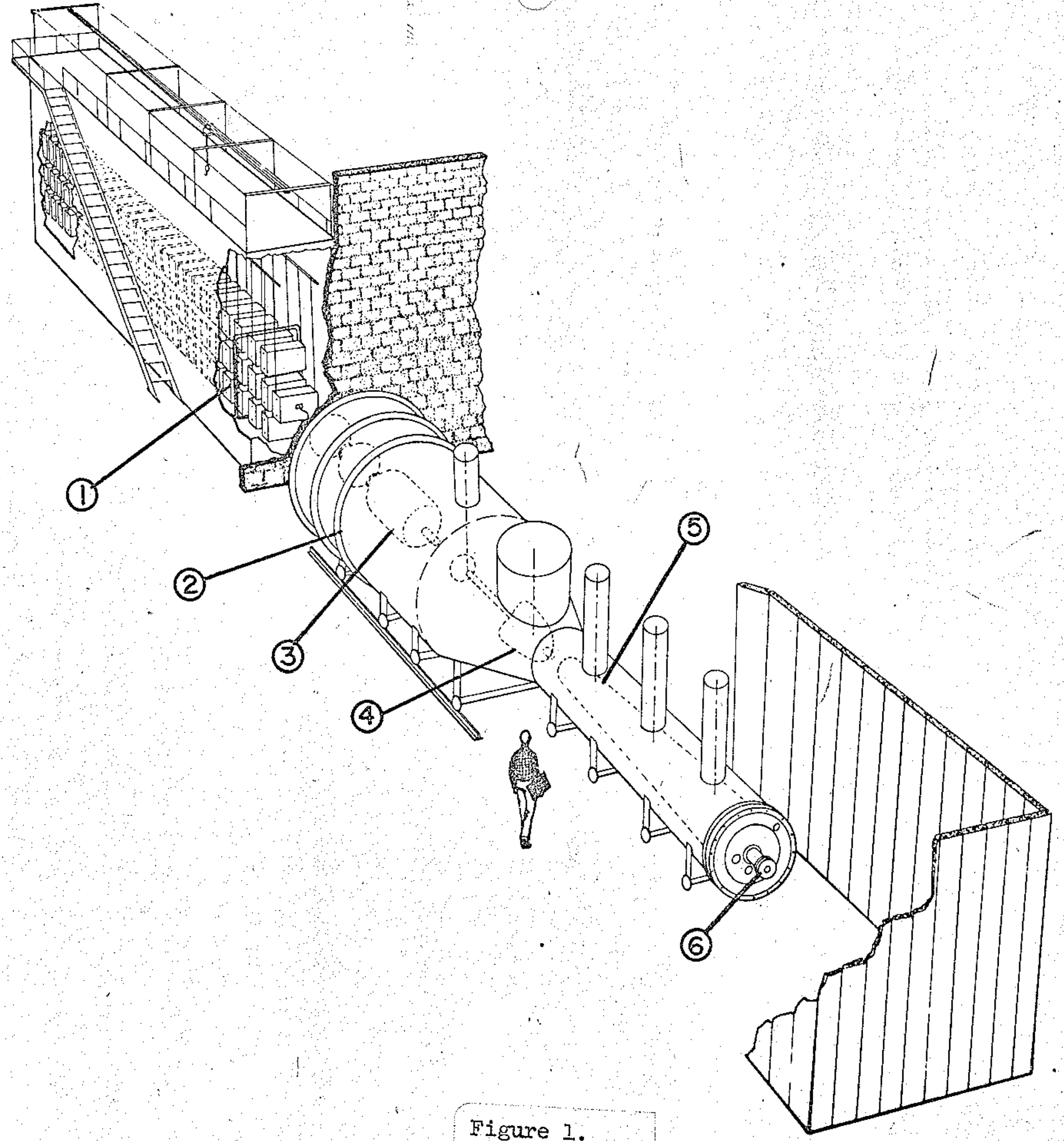


Figure 1.

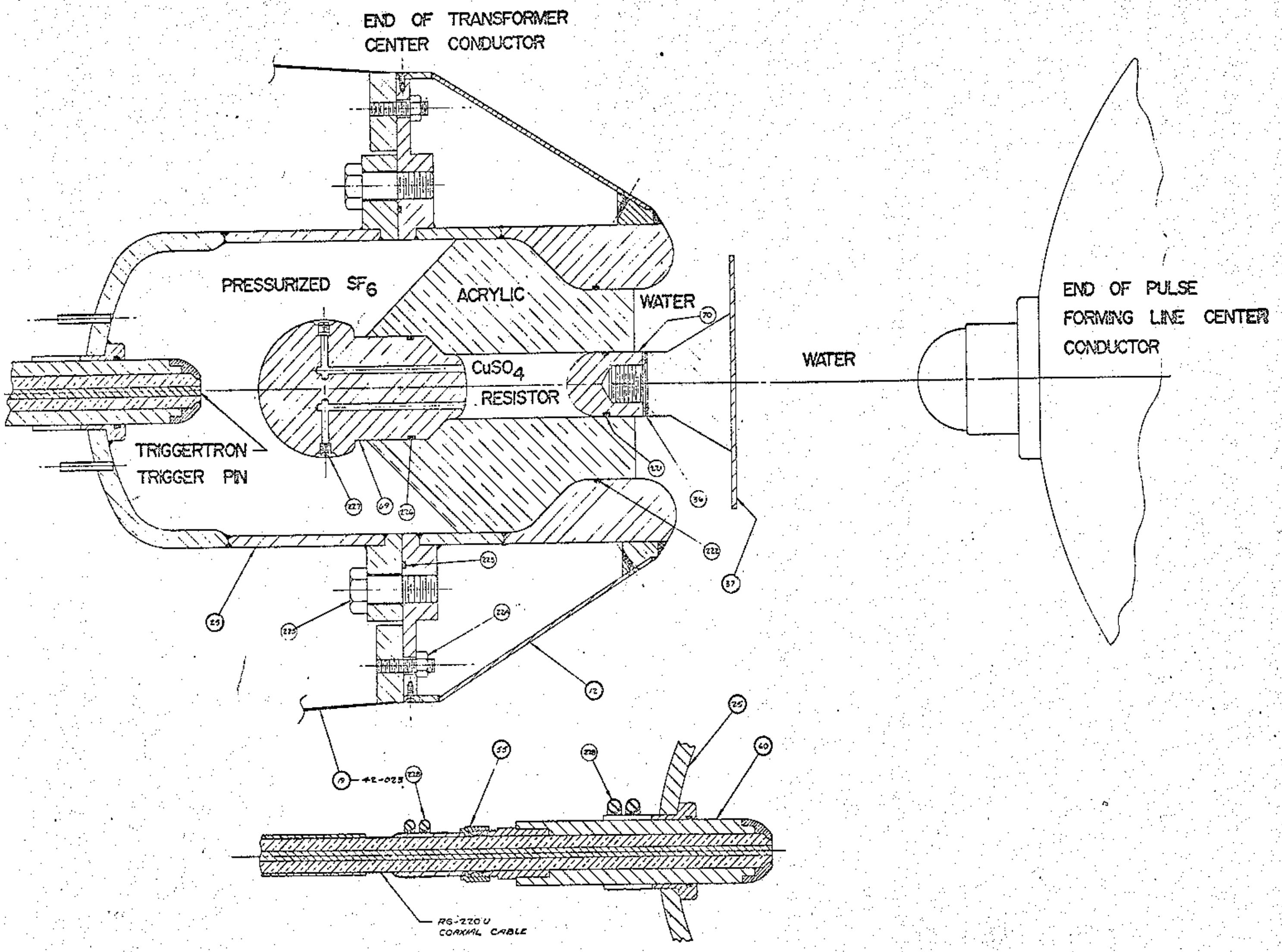

END OF TRANSFORMER
CENTER CONDUCTOR
PRESSURIZED SF_6
ACRYLIC
WATER
$CuSO_4$
RESISTOR
TRIGGERTRON
TRIGGER PIN
WATER
END OF PULSE
FORMING LINE CENTER
CONDUCTOR
70
221
36
222
37
227
69
224
225
223
224
25
72
19
42-025
228
55
228
25
40
RG-220U
COAXIAL CABLE

Figure 2.

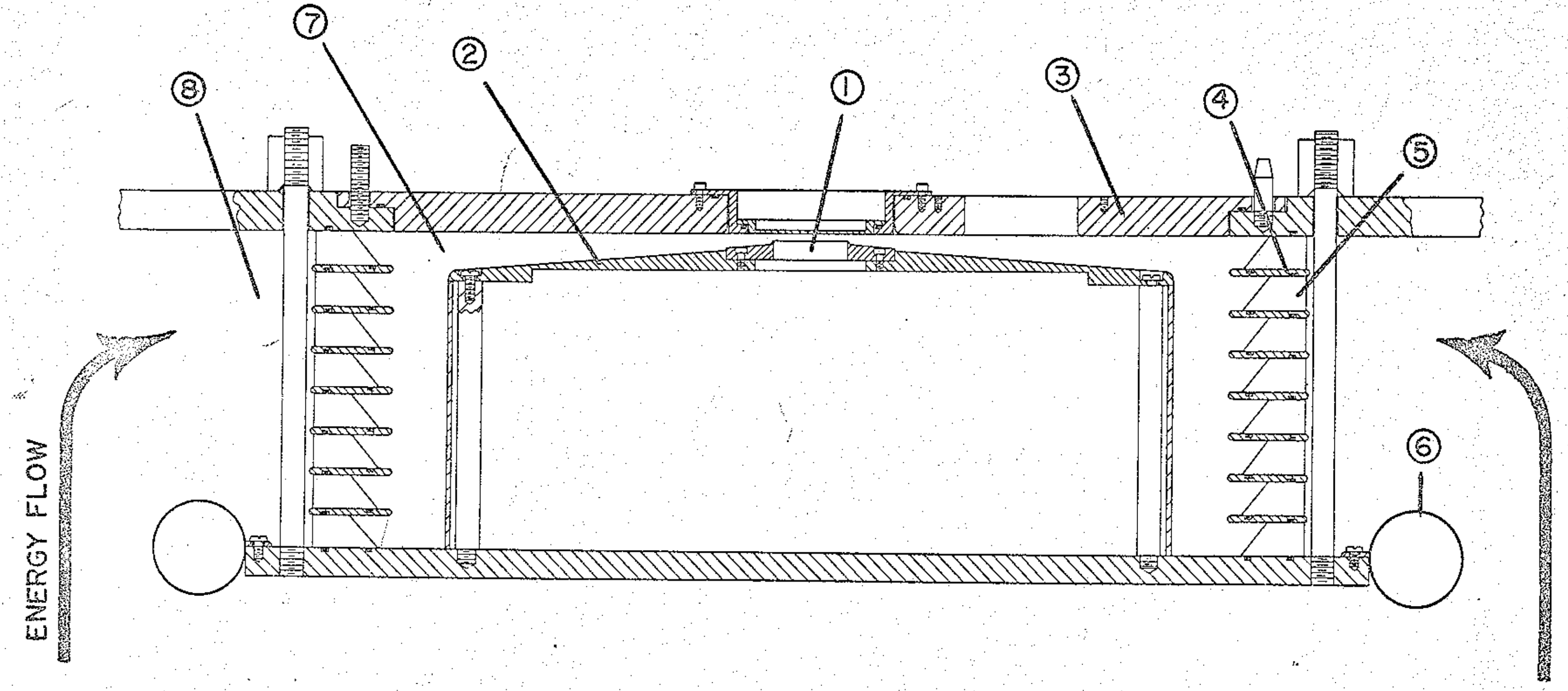
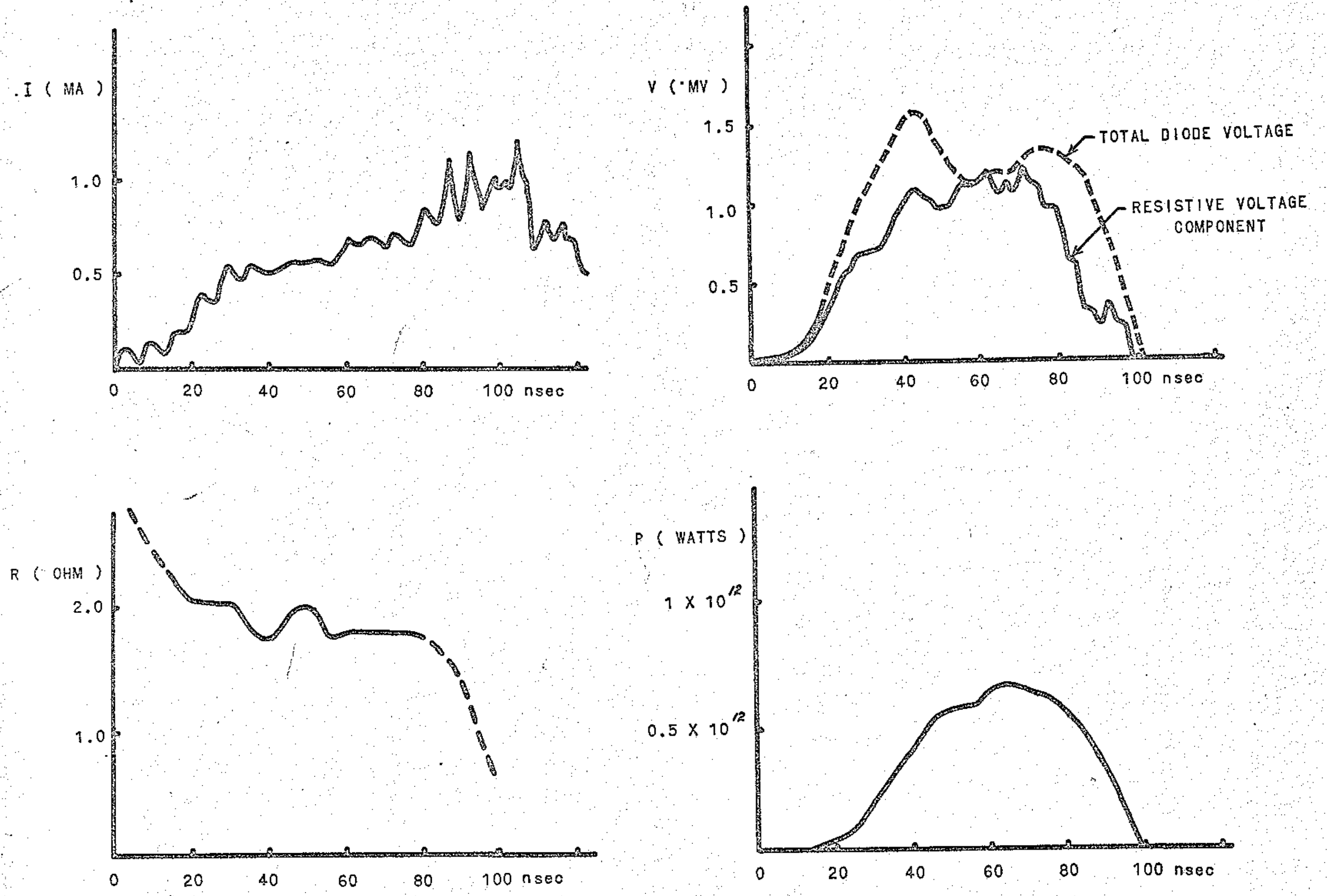


Figure 3.



.I (MA)
1.0
0.5
0
20
40
60
80
100 nsec
V (MV)
1.5
1.0
0.5
TOTAL DIODE VOLTAGE
RESISTIVE VOLTAGE COMPONENT
0
20
40
60
80
100 nsec
R (OHM)
2.0
1.0
0
20
40
60
80
100 nsec
P (WATTS)
1 X 10^12
0.5 X 10^12
0
20
40
60
80
100 nsec

Figure 4.

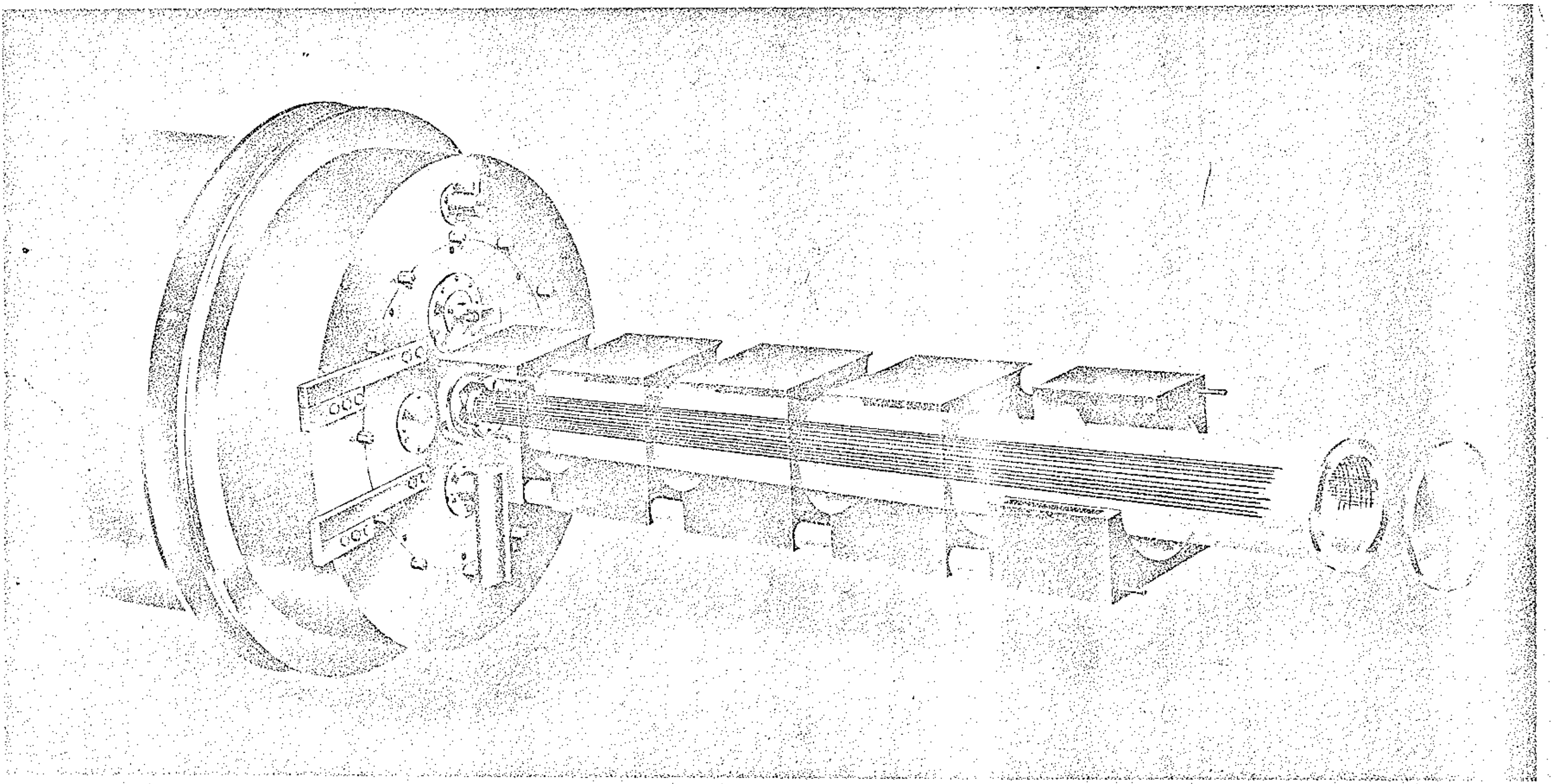


Figure 5.

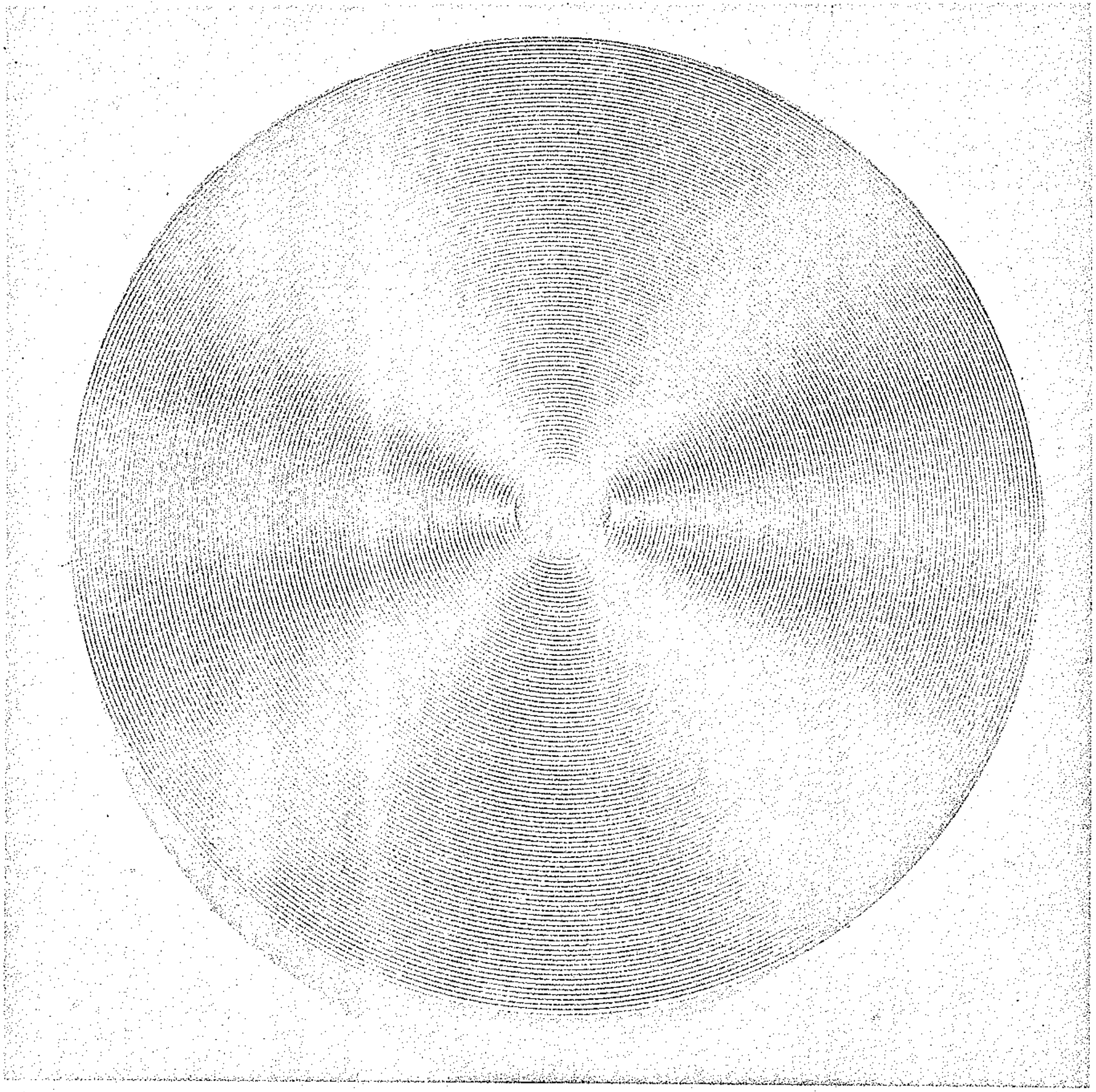


Figure 6.

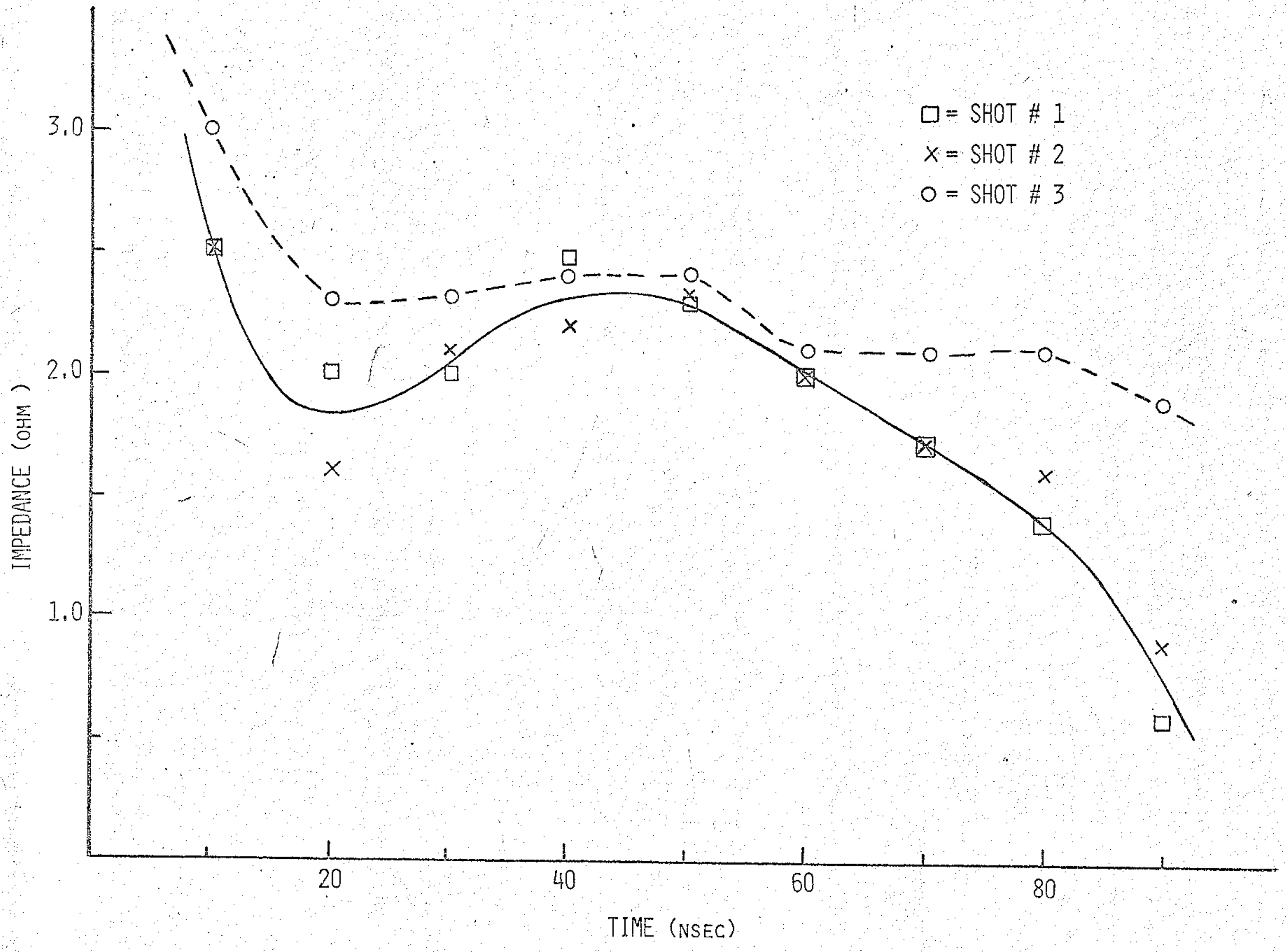


Figure 7.

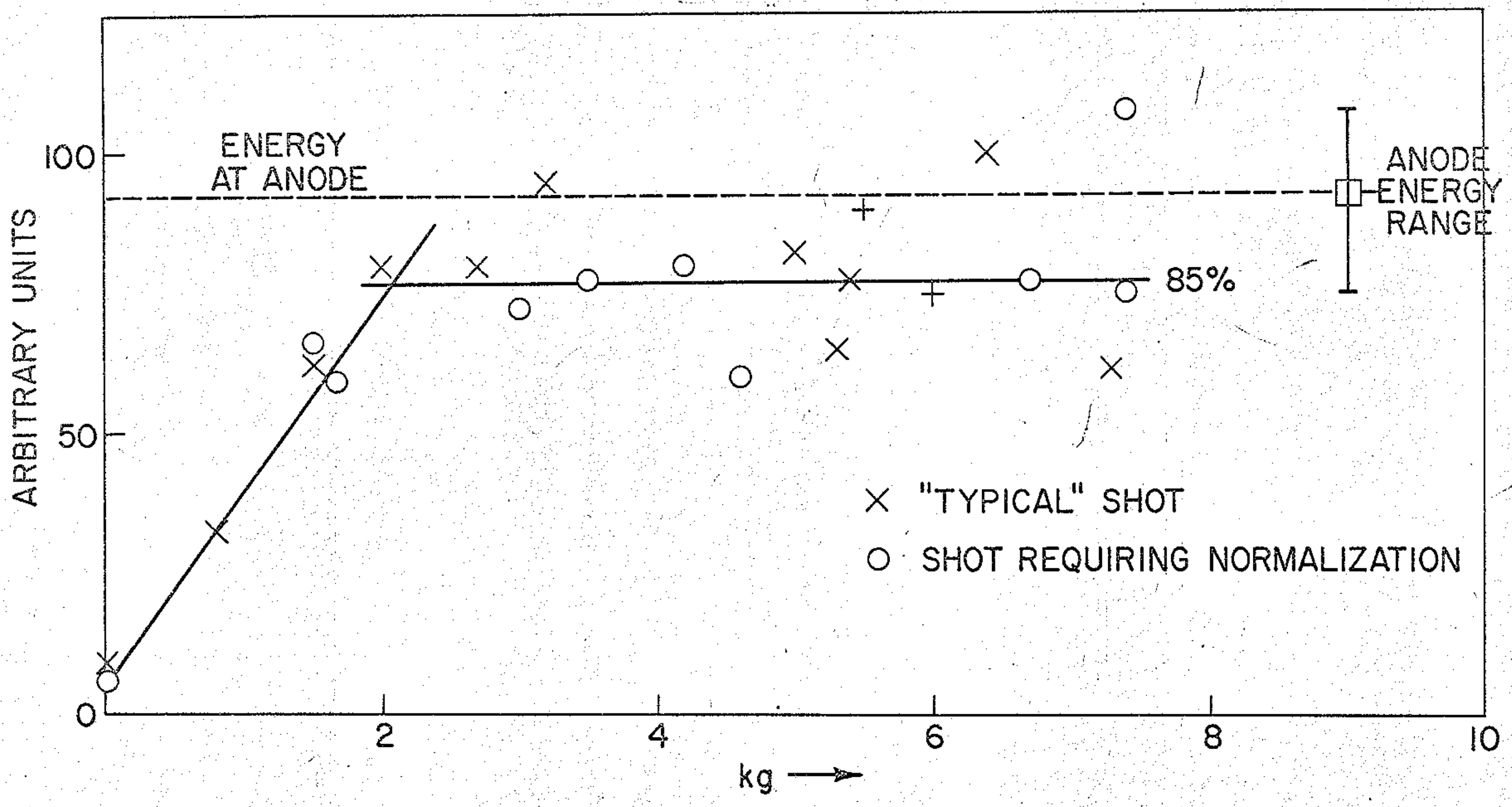

ENERGY
AT ANODE
ANODE
ENERGY
RANGE
85%
ARBITRARY UNITS
100
50
0
2
4
6
8
10
kg →
× "TYPICAL" SHOT
○ SHOT REQUIRING NORMALIZATION

Figure 8.

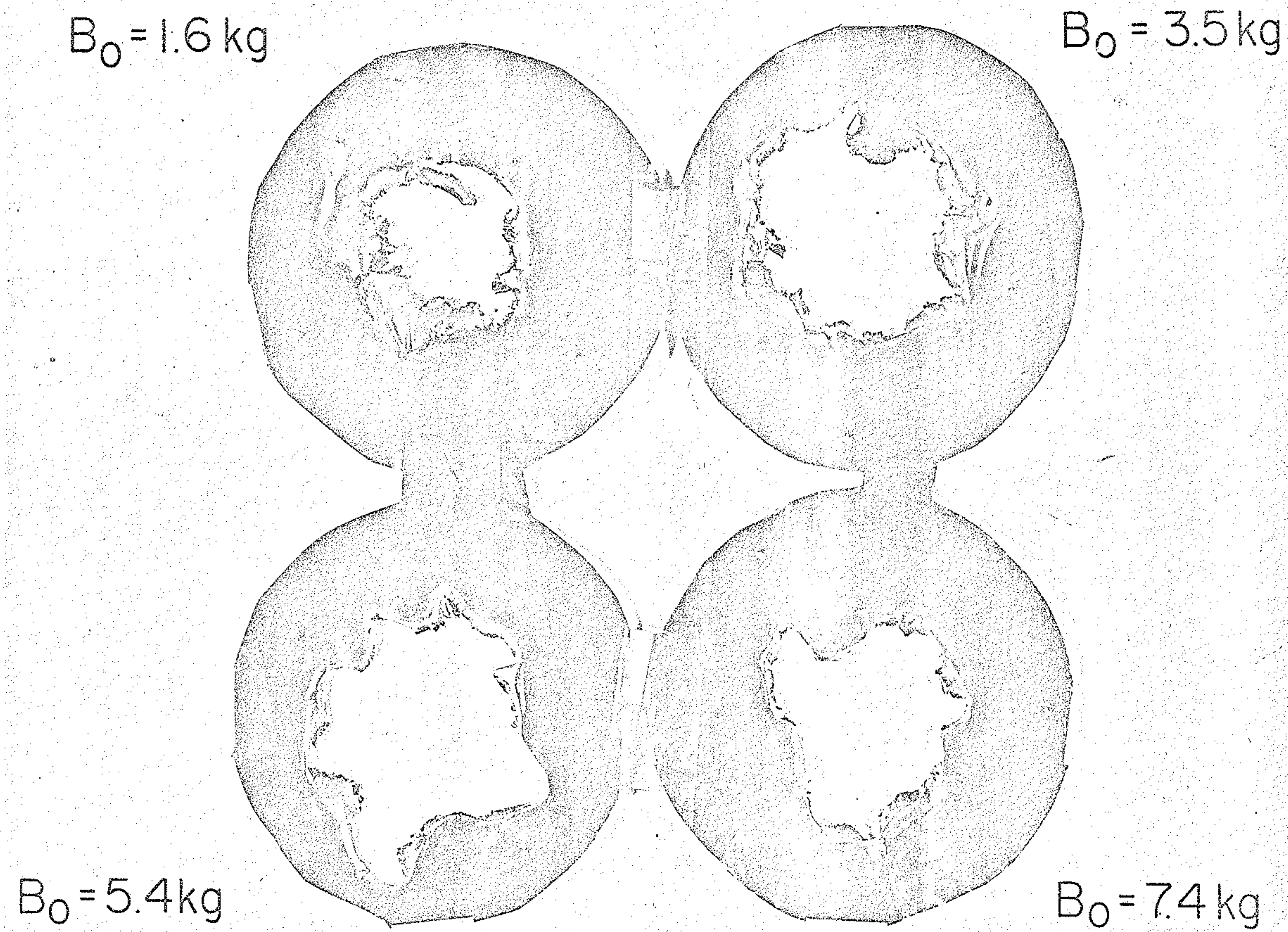


Figure 9.

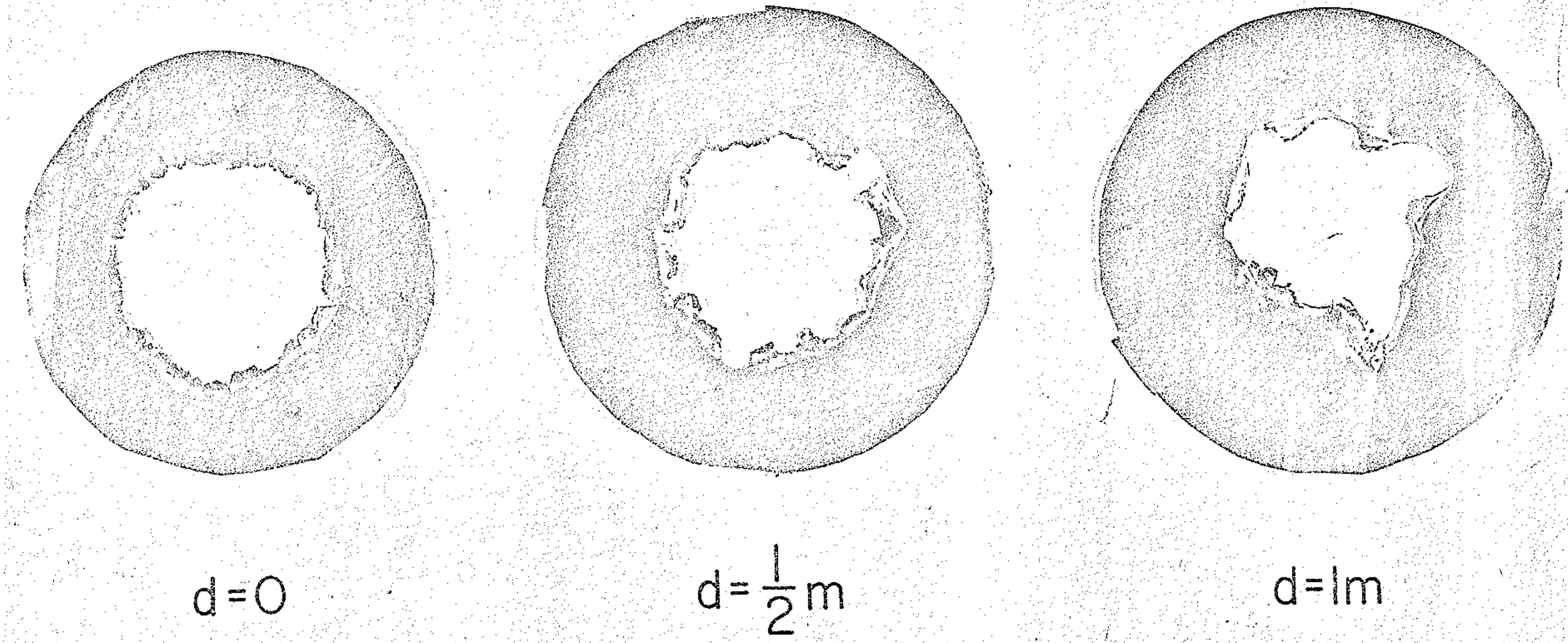


Figure 10.

Table 1.

ELECTRICAL PARAMETERS OF THE GAMBLE GENERATORS

		Gamble I	Gamble II
Marx Generator	Capacity	12 nF	4.1 nF
	Output Voltage	3.3 MV	6.0 MV
	Energy Stored	66 kJ	228 kJ
Intermediate Storage Capacitor	Capacity	8.7 nF	7.4 nF
	Voltage	3.7 MV	6.0 MV
	Energy Stored	60 kJ	133 kJ
Pulse Forming Line	Transmission Line Impedance	4.0 Ohms	5.8 Ohms
	Capacity	6.25 nF	4.3 nF
	Voltage	4.0 MV	6.8 MV
	Energy Stored	50 kJ	100 kJ
	Output Pulse Duration	50 nsec	50 nsec
Coaxial Transformer	Input Impedance	4.0 Ohms	5.8 Ohms
	Output Impedance	1.53 Ohms	1.53 Ohms
	Output Voltage	1.0 MV	1.0 MV
	Design Load	1.0 Ohms, 20 nH	0.6 Ohms, 20 nH
	Energy Delivered to Load	32 kJ	60 kJ