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THE STREAMER CHAMBER*

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The continuing interest in spark chamber development has recently led to a new device for making visible the tracks of subatomic particles

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As early as the fifth century B.C., Anaxagoras and, a generation later, Democritus were postulating a universe consisting of empty space and an infinite number of indivisible and invisible particles, unchangeable and imperishable but differing from one another in form, position, and arrangement. Since that time, the nature of matter has remained a central problem in man's quest to understand his environment. It is this tradition, manifest in the work of Planck, Einstein, Rutherford, Bohr, Heisenberg, Schrödinger, Dirac, and many others, which has led to our present understanding that matter does, in fact, consist of atoms, that atoms in turn consist of nuclei surrounded by orbiting electrons, and that even the most complicated nuclei consist only of protons and neutrons (see "Ordinary Matter," by Gerald Feinberg; SCIENTIFIC AMERICAN, May 1967). As the direct heirs to this tradition, modern elementary particle physicists are now concerned with the nature of protons, neutrons, and electrons as well as with the nature of well over a hundred other subatomic "particles" which have appeared unexpectedly on the scene (see "Strongly Interacting Particles," by Geoffrey F. Chew, Murray Gell-Mann, and Arthur H. Rosenfeld; SCIENTIFIC AMERICAN, February, 1964).

Among the principal tools available to the elementary particle physicist are high energy particle accelerators (see "Particle Accelerators," by Robert R. Wilson; SCIENTIFIC AMERICAN, March, 1958) for producing subatomic particles and a variety of detectors for studying those particles produced. In fact, the search for new and more useful detectors has been carried on as vigorously and with as much success as the related program to develop new accelerators of higher energy and higher intensity. In both cases, modern day physicists have frequently solved their problems by finding "practical" applications for the results of "basic" research from an earlier period. The streamer chamber, a new and very promising elementary particle detector, is an excellent example. Essentially it is an application of the work done by Townsend, Loeb, Meek, Raether, and others on spark formation and electrical discharge in gases, most of the relevant research in this field having been carried out prior to World War II.

The fundamental fact, upon which all elementary particle detectors except Cerenkov counters depend, is this: that charged particles passing through matter interact with atomic electrons to produce free electrons and positive ions. The actual number of ionizing collisions is relatively small (e.g., 10 ions are formed per cm of path in hydrogen gas); and some additional mechanism is needed before the ions and electrons signaling the passage of a charged particle can be observed. Particle detectors differ principally in the method by which the small initial ionization "signal" is amplified.

There are essentially two broad classes of particle detectors: "counters" in which the original signal results ultimately in an electrical pulse which can be analyzed and counted electronically and "track detectors" in which the amplification process is localized along the ionization path, making this path visible and photographable. In general, counters are used to detect single particles at a high rate, perhaps up to 10 million counts per second or higher. Track detectors are normally limited to a few events per second, but they are capable of detecting simultaneously and in great detail all of the charged particles involved in each event.

In the earliest successful track detector, the cloud chamber, invented by C. T. R. Wilson in 1911, the ions left by the passage of a charged particle serve as condensation centers for the supersaturated vapor which is produced when the gas filling the chamber is allowed to expand. The droplets formed in this way can be photographed to provide a visual record of the passage of the original ionizing particle. Similarly, the bubble chamber, developed by D. A. Glaser in the early

1950's, is cycled between the liquid and gaseous phases in such a way that the residual ions serve as vaporization centers for the formation of bubbles within the chamber liquid. In both the cloud chamber and the bubble chamber, the amplification mechanism does not substantially change the total number of ions; and in both, an external light source must be used to illuminate the droplets or bubbles.

The spark chamber (see "The Spark Chamber," by Gerard K. O'Neill, SCIENTIFIC AMERICAN, August, 1962) is a track detector in which the total number of ions is amplified until the light emitted as a result of the secondary ionization is sufficiently intense to be photographed directly. This ion multiplication is achieved by applying a high voltage pulse across a series of parallel conducting plates in such a way that bright sparks are produced between the successive plates through which the original particle has passed. Each spark occurs as a result of an ionization cascade initiated by a single, or at most by a few primary electrons The amplification energy is supplied by the high voltage pulse.

Each of the three track detectors mentioned is currently in use; and each has advantages and disadvantages, depending upon the particular application. An advantage of the cloud chamber is that it can be triggered by counters which are arranged to detect particles which have passed through the chamber as well as those produced in the chamber. This permits the electronic selection of a few interesting events from among the many that are not, and it sharply reduces the number of photographs which must be taken and analyzed before an interesting event is found. A modern bubble chamber experiment may, for example, involve as many as one million pictures in which perhaps ten thousand events are collected. In such an experiment, the cost of the data analysis alone is obviously considerable. The most serious disadvantages of the cloud chamber are the slow cycling rate, typically one cycle per 20 sec, and the fact that the ionization track persists for a significant fraction of a second. Diffusion cloud chambers can be continuously sensitive but still suffer from long track persistence.

Bubble chambers can be cycled more rapidly than cloud chambers. Repetition rates of 1 cycle per second are common, and rates as high as 10 cycles per second have been achieved in some small chambers. This is important in utilizing to the utmost the capabilities of high energy particle accelerators with repetition rates rather faster than the cycling rate for cloud chambers. In addition, a variety of liquids has been used in bubble chambers, including hydrogen, helium, propane, and xenon; and this adds considerably to the range of applications. Finally, the interaction rates in the relatively dense liquid filling a bubble chamber are far higher than those in the vapor initially present in a cloud chamber.

Standard spark chambers combine some of the advantages of both the cloud chamber and the bubble chamber. In particular, spark chambers can be triggered (Fig. 1); but unlike the cloud chambers, the sensitive time can be as short as one millionth of a second so that spurious events which occur before or after the triggering event are not seen. The cycling rate can, in some cased, be as high as 1000 cycles per second, i.e., much higher than for either the cloud chamber or the bubble chamber; and like the bubble chamber, a wide range of target materials can be used. Spark chamber plates can be made of almost any metal or conductor, and many non-conducting materials can easily be imbedded within thin-walled aluminum plates, if desired. It is not possible to see precisely the origin of an event occurring within a spark chamber plate; but if many thin plates are used, this is not a serious disadvantage.

The spark chamber, unlike the cloud chamber and bubble chamber, has evolved slowly over a period of perhaps fifteen years and is the result of contributions by a number of different physicists including J. W. Keuffel of the United States, M. Conversi and A. Gozzini of Italy, T. E. Cranshaw and J. F. de Beer of Great Britain, and S. Fukui and S. Miyamoto of Japan. The first spark chamber experiments were carried out by B. Cork and, independently, by J. L. Cronin of the United States about 1960. Shortly thereafter, it was shown by G. K. O'Neill of the United States and by others that spark chambers could be made to work in strong magnetic fields. This permits the momentum of each charged particle to be determined from the track curvature in the magnetic field, just as in the case of cloud chambers and bubble chambers.

Although the standard spark chamber, as employed by Cork and by Cronin, is still the type most widely used, a number of promising variations are being developed. On the one hand, the unique advantages of the spark chamber, particularly the fact that it can be operated at a high repetition rate and can be triggered in much less than one millionth of a second, are being strongly enhanced and widely exploited. This had led to a new class of detectors, the "digitized spark chambers," in which the spark location is not determined photographically but instead is made available as an electronic signal which can be stored on tape or sent directly to a computer. The analysis can then proceed almost as rapidly as the data arrive. Digitized spark chambers tend to combine the high speed of conventional counters with the detailed sensitivity of track detectors.

At the same time that the advantages of the spark chamber are being exploited, the original disadvantages, as compared to the bubble chamber, are being eliminated, or at least reduced. What one wants in many instances is a triggered bubble chamber. A brief summary of some of the differences in the two devices will help to make this point clear.

We should begin this summary by noting that bubble chambers can be filled with pure hydrogen so that the only nuclear reactions possible are those involving elementary particles and hydrogen nuclei (protons). While it is possible to fill the hollow plates of a spark chamber with hydrogen, this is so difficult and hazardous that no experiments have been done as yet using this technique. A second advantage of the bubble chamber is that its response is isotropic. Spark chambers normally have a poor sensitivity for tracks which are within 45° or so of being parallel to the plates.

A third advantage of the bubble chamber is that the ionization trails are quite fine so that the location of points along each track can be very precisely determined. In ordinary spark chambers, the track appears as a series of spark segments. The finite length of these segments and their scatter about the true ionization path result in somewhat poorer spatial resolution. A final point is that bubble chambers are sensitive to almost any number of tracks from the same event, while spark chambers have a limited multiple-track efficiency after typically four to six tracks. This is particularly serious in studying high energy events which tend to involve large numbers of interaction products. At the same time, higher energies demand better spatial resolution, as well as a larger sensitive volume. This is because the track curvatures of high energy particles passing through a magnetic field are less. Unfortunately, as one reduces the plate spacing in a conventional spark chamber to improve the spatial resolution, the multiple-track efficiency becomes even worse.

Late in 1963, A. I. Alikhanian and his collaborators in the Soviet Union reported the development of a "wide-gap spark chamber" in which the magnitude and duration of the high voltage pulse permit spark formation and a continuous discharge along a particle path which necessarily extends between the high voltage plates. This device avoids the segmented tracks of the conventional spark chamber and in some cases allows the vertex of an interaction which occurs in the chamber gas to be seen. The wide-gap spark chamber is by no means isotropic; but it is capable of high resolution and is thus a respectable first step towards a triggered bubble chamber.

Early in 1964, another group of Soviet physicists, led by G. E. Chikovani, reported that they had succeeded in developing a "wide-gap streamer chamber." In this device, the parallel plates are again widely spaced; but the high-voltage discharge, which originates simultaneously at a number of points along the ionization path, is arrested at an early stage. This requires a driving pulse of much shorter duration than is used with either wide-gap or conventional spark chambers. The resulting track (Fig. 2) when viewed perpendicular to the field, appears as a series of streaks (streamers) whose length and brightness depend upon the parameters of the high voltage pulse. When viewed through transparent electrodes along the electric field and parallel to the streamer axes, the track appears as a series of dots similar to a tract in a bubble chamber.

The streamer chamber is superior to the wide-gap spark chamber from the point of view of multiple track efficiency and of track-following capability. The vertices of events which occur in the gas volume between the plates of a streamer chamber are clearly seen, whether or not the ionization paths intercept both plates. Since the ion multiplication is halted in the case of the streamer chambers before a complete breakdown occurs, the light intensity is quite low. This is the most serious disadvantage of the streamer mode of operation.

Work on streamer chambers at the Stanford Linear Accelerator Center (see "The Two-Mile Electron Accelerator," by Edward L. Ginzton and William Kirk, SCIENTIFIC AMERICAN; November, 1961) was begun by F. Bulos and his collaborators shortly after the early Soviet articles appeared. Originally this effort was motivated by the considerable promise which these devices, as compact, isotropic detectors of high resolution, held for colliding beam experiments (see "Particle Storage Rings," by Gerard K. O'Neill, SCIENTIFIC AMERICAN, November, 1966) at energies well above one billion electron volts. Within the next year, R. Mozley and A. Odian in a second group at SLAC were planning to incorporate a wide-gap streamer chamber of small dimensions into photoproduction experiments designed around conventional spark chambers. As the advantages and feasibility of the streamer chamber approach became more evident this chamber grew in size from this modest beginning until it filled entirely the large magnet volume reserved originally for the conventional chambers. A. Odian and F. Villa, in constant communication with F. Bulos and R. Mozley, were the SLAC physicists most deeply involved in this program.

Like the wide-gap and conventional spark chambers, streamer chambers have an important advantage over bubble chambers, particularly as far as SLAC is concerned: since they are tirggered, they can use the full 360-cycle repetition rate of this recently completed 20 billion electron volt accelerator. On the other hand, the beam from the two-mile accelerator can be switched into several different experimental areas on a pulse to pulse basis. If enough intensity is available in each pulse, a bubble chamber can be operated efficiently at one pulse per second without seriously perturbing the rest of the experimental schedule. It is therefore quite likely that in the near future a visitor to SLAC would find bubble chamber, streamer chamber, and spark chamber experiments going on simultaneously, permitting together a more effective use of the accelerator than would be possible if only one of these track detectors were available.

Let us consider now what happens when an electric field acts on an electron left by an ionizing charged particle. For sufficiently high fields, the energy lost by "elastic" collisions between the electron and the atoms in the gas is negligible; and the electron continues to accelerate under the influence of the field until it has sufficient energy to undergo "inelastic" collisions and to produce secondary ions and additional free electrons. Electrons, rather than ions, are responsible for the multiplication process since the ions (which are also accelerated by the field, but in the opposite direction) are some 10,000 times more massive than the electrons and typically have velocities 100 times less.

Some idea of the great speed with which the initial multiplication process occurs can be gained by noting that electrons drift at a rate of about 1 millimeter in 10 billionths of a second, or about 1/3000th of the speed of light. Photons emitted during the initial ionizing collisions will thus travel a distance of only 3 meters in the time that it takes the primary "avalanche" to grow to a length of 1 millimeter. During this time, the exponential increase in the number of electrons will involve some 20 generations and will result in perhaps 100 million free electrons and ions!

The multiplication factor of 100 million represents an impressive amplification of the original small signal. Furthermore, the total number of photons emitted is comparable with the number of ions and free electrons formed. Additional amplification is, however, required before direct photography with available films is practical. In this connection, it is interesting to note that H. Raether succeeded in 1937 in producing avalanches (and streamers) in a cloud chamber beginning with a single free electron (Fig. 3). The additional amplification provided by the condensation of the cloud chamber vapor into droplets was sufficient to permit direct photography in this classic series of experiments.

After a certain point, the space charge developed by the avalanche itself transforms the avalanche into a streamer. A striking feature of this transformation is the rapid longitudinal extension of the streamer, which occurs at a rate of at least 1 centimeter in 10 billionths of a second, or about 1/300th of the speed of light. This is an order of magnitude faster than the drift velocity of the electrons and the rate of extension of the primary avalanche, and it indicated that a different mechanism or mechanisms are involved.

The critical point in the development of a streamer occurs when the density of the electrons is so high that the electric field due to these electrons is a significant fraction of the applied field. After the primary avalanche is formed, the dominant process is ionization by photons produced in the original avalanche. These photons are emitted isotropically and produce other electrons and still more photons in the gas by photoionization. The additional electrons produce localized secondary avalanches, particularly near the positive and negative tips of the original avalanche where the electric field is intensified by the additional space charge. The new avalanches feed the tips of the original streamer symmetrically, leaving behind space charge which extends the streamer symmetrically in the directions of both the positive and the negative high voltage plates. The threshold for streamer breakdown is set by the condition that the secondary avalanches be self sustaining, e.g., that the electrons feeding the positive tip of the primary avalanche, and thus neutralizing it, leave behind positive ions equal in density to those that existed in the primary avalanche. The additional amplification obtained when the initial avalanche transforms itself into a streamer is sufficient to permit direct photography, using the ionization photons.

In the case of streamer chambers, the applied electric field is 5 - 10 times the field required for static breakdown; and the plate-to-plate discharge which occurs in conventional spark chambers is prevented only by the extremely short pulse duration, typically 10 billionths of a second. The magnitude of the electric field required depends upon the streamer chamber gas chosen and the gas purity, as well as upon the pulse duration. For the 10 billionth of a second pulse duration assumed here and for the 90% neon - 10% helium gas mixture commonly used in spark chambers, the required field is 15-20 thousand volts per centimeter when the impurities in the gas are less than 1/2% This pulse will normally be applied to the plates of the streamer chamber within somewhat less than one millionth of a second, just as in the case of standard spark chambers.

The basic conditions under which photographable streamer tracks will be formed are now clearly understood. If, for example, we wish to observe streamer tracks in a chamber having a 30-centimeter gap between two parallel high voltage plates, we must first fill the desires sensitive volume with neon-helium gas and then apply a 450-600 thousand volt pulse lasting only 10 billionths of a second and occurring within one millionth of a second after the initial ionization path is formed by the passage of a charged elementary particle. Conventional counters and electronics can be used to detect the passage of the particle; the major difficulty lies in generating the fast, high voltage pulse. This problem is best approached by separating the pulse-generating and pulse-shaping functions. Large generators do not usually produce fast pulses.

The most widely used high voltage pulse generator is that invented by E. Marx about 1924 (Fig. 4). The basic principle upon which the Marx generator is based is really quite simple. One begins a cycle by charging a number of capacitor stages in parallel using a dc high voltage supply, and one completes the cycle by discharging these capacitors in series so as to add the individual voltages of each stage. A 34-stage generator charged to 40 thousand volts per stage is thus able to produce a pulse of more than 1.3 million volts. Capacitors capable of withstanding 40 thousand volts are readily available, as are power supplies capable of generating a dc voltage at this same level.

The rearrangement of the electrical current path is accomplished in the Marx generator by a series of spark-gap "switches" which can hold off the dc charging voltage until the first gap is externally triggered, for example, by conventional counters. Thereafter, the voltage across each succeeding gap is the sum of the charging voltages across all of the previous gaps. The additional voltage assures the participation of all succeeding stages in the discharge. If both positive and negative charging voltages are used, the number of spark gaps required is half the number of capacitor stages.

The limitation of the Marx generator, at least as far as streamer chambers are concerned, is that the discharge time, through many stages and many spark gaps in series, is relatively long. As a result, the output pulse duration in a large Marx generator capable of putting out pulses in the million-volt range is perhaps 100 billionths of a second instead of only 10 billionths of a second, as required for short streamers. Physicists working on streamer chambers at SLAC were just beginning to appreciate the seriousness of this rather fundamental limitation when G. E. Chikovani and his collaborators announced that they had found a way of circumventing it.

The first pulse-shaping network (Fig. 5) to be used with streamer chambers consisted essentially of a capacitor capable of withstanding the full output voltage of a 200 thousand volt Marx generator. When sufficient energy had been stored in this capacitor, a single high voltage spark gap was discharged to "switch" this stored energy onto the plates of a wide-gap streamer chamber. The slow discharge of the Marx generator, which continues after the peak voltage has been achieved, can then be shunted through a second spark gap, called a "shorting gap" or a "crow-bar gap," so that only the fast pulse reaches the plates of the chamber. It is important to note that the parallel plates of a streamer chamber constitute a capacitor themselves. Thus this early (meaning early 1964) pulse shaping technique replaces the large capacitance and high inductance of the Marx generator with an intermediate capacitance and the small inductance of a single-spark gap. The result is a better match of the electrical characteristics of the drive system and the streamer chamber.

Because of the extreme brevity of the high voltage pulse needed to produce short streamers, the time required for this pulse to travel from one end of a large chamber to the other can be longer than the pulse itself. It is therefore appropriate to consider large chambers, not as capacitors, but rather as transmission lines through which an electromagnetic wave of radio frequency is propagated at nearly the speed of light. In this case, the ideal pulse shaping network is another transmission line coupled to the streamer chamber with complete "impedance matching" throughout.

It is quite possible to build a capacitor in the form of a transmission line and to charge this capacitor with the "slow" output pulse from a Marx generator. If this line is now discharged through a single spark gap into a second, matching transmission line which is coupled to a streamer chamber, an electromagnetic wave will be produced. This pulse rises to its maximum voltage in the time required to fire the spark gap, typically one or two billionths of a second; and it holds this voltage for the time required by the pulse to travel the length of the charged line. The tail end of the pulse is also sharply defined. The disadvantage of this system is that half the charging voltage is lost in matching the impedances of the two transmission lines.

The "voltage-doubler circuit" invented by Blumlein during World War II provides a means by which the full charging voltage can be achieved with a completely matched transmission line. In the "Blumlein line" or "Blumlein," as it is commonly called, the time required for the pulse to reach its peak voltage is again determined by a spark gap, the major differences being that an additional electrode is used and that the pulse duration is twice the time required for an electromagnetic wave to travel the length of this electrode. This last point is of little consequence since the length of the charging electrode can easily be adjusted to give pulses of the required duration, just as the length of the charging member of the matched transmission line could be adjusted in the previous case.

The Blumlein is an ideal pulse-shaping network for large streamer chambers and represents a significant advance in this field. Much of the credit for this development at SLAC must be shared with J. C. Martin and I. Smith of England, both of whom visited the Linear Accelerator laboratory to participate in this program.

The discussion thus far has been restricted to streamer chambers having a single wide gap between two parallel plates. In practice, it may be more convenient to use a pair of gaps defined by three parallel plates (Fig. 6). The center plate then serves as the high voltage electrode, while the outer plates remain at ground potential. The outer ground electrodes can then be joined at the sides of the chamber to form a completely enclosed, pseudo-coaxial transmission line (Fig. 7). Not only does this arrangement double the chamber volume without doubling the required high voltage, but in addition, the grounded enclosure shields the outside world from the intense radio frequency radiation. A completely enclosed, matching Blumlein structure is also possible.

Since a large streamer chamber is itself a transmission line, it too must be "terminated" in a matched load which absorbs the power and which does not "reflect" secondary electromagnetic waves back through the chamber. The outer grounded enclosure can then be walled off beyond the end of the central high voltage electrode where the pulse termination takes place. This completes the radio frequency shield.

As we have already indicated, streamer chambers are normally viewed directly through transparent plates, not through the gaps between the plates, as with conventional spark chambers.

"Transparent" plates for streamer chambers can be constructed by stringing piano wire across a window-frame supporting structure in the direction in which the electromagnetic wave is expected to propagate. A wire separation of 1 centimeter with a wire diameter of a quarter of a millimeter seems to be satisfactory. The neon-helium gas mixture can be contained within two cells which have transparent windows made of thin, clear sheets of Mylar or other plastic. The windows and the neon-helium gas mixture must be spaced several wire diameters away from the wires to prevent flares from forming near the wires where the electric field is particularly high. The wires, although "transparent" to light, provide an effective shield for the radio frequency wave which has characteristic wave length components that are much longer than the wire separation.

For experiments in which the events of interest occur outside of the streamer chamber, the exact composition of the chamber gas is of little importance, and almost any target material can be used. Solid nonconducting materials can also be installed as targets within the sensitive volume of the chamber and have little effect upon the performance unless the target dimensions approach the gap spacing. In these two classes of experiments, those with external targets and those with solid targets within the sensitive volume, the streamer chamber should compete favorably with conventional spark chambers on the basis of the streamer chamber's superior multiple track efficiency, their higher spatial resolution, and their excellent isotropy and track-following capability.

In many applications, the gas filling of the streamer chamber would provide an excellent target material. D. Benaksas of France and R. Morrison of Canada, working at Stanford University, have recently completed a study of "triplet production" in which an incident high energy photon, or gamma ray, strikes an electron in a neon atom and generates a positron-electron pair in an "electromagnetic interaction." The characteristic signature for this event--a positron and two electrons suddenly materializing from the same vertex with no sign of the neutral incident photon--is easily recognized in the isotropic neon-helium medium (Fig. 8). Similarly, B. Hughes and his collaborators at Princeton are using a streamer chamber to study the decay of neutral K mesons, a process which involves a "weak interaction." The decay within the chamber is spontaneous and does not depend in any way upon the nature of the chamber gas (Fig. 9).

Streamer tracks have also been observed in pure hydrogen gas as well as in pure helium by V. I. Komarov and O. V. Savchenko in the Soviet Union. As in the case of hydrogen bubble chambers, the use of hydrogen gas in streamer chambers would permit experiments in which the only nuclear reactions possible are those involving incident elementary particles and target protons. The difficulty here is that the required electric field is about three times that for neon.

In the high energy photoproduction experiments now in progress at SLAC (Fig. 10), it is possible to produce a high energy photon beam collimated to a diameter of less than 3 millimeters in the experimental area. This beam passes cleanly through a 12-millimeter diameter, thin-walled Mylar "straw" which is mounted in the upper neon-helium cell of a large double-gap streamer chamber. The Mylar straw can be filled with almost any gas that is available. The range of target materials is thus quite broad and rather more flexible than for either bubble chambers or conventional spark chambers. Furthermore, this range includes the target elements of greatest interest to physicists: hydrogen with a nucleus consisting of one proton; deuterium (an isotope of hydrogen) with a nucleus consisting of one proton and one neutron; and the various isotopes of helium with only two protons.

The price paid for the separate gas target, from the point of physics, is the loss of sensitivity in the 12-millimeter diameter target region. Since this region consists of a thin gas, rather than a dense solid or liquid, only particles of quite low energy fail to penetrate into the sensitive volume of the chamber. Such particles are also lost in bubble chambers since their "tracks" in bubble chamber liquids are too short to be detected. Furthermore, the magnetic field is strong enough so that even high energy particles produced at 0^{o} with respect to the beam direction are deflected into the neon-helium region. It is of some importance that the actual vertices of events occurring in the target are not seen, but an extrapolation of the observed tracks into the target region allows a precise reconstruction of this portion of the event history.

A summary of the "vital statistics" for the 2-meter streamer chamber developed at SLAC will give some idea of the extent to which this new track detector has evolved in the last four years. The sensitive volume of the SLAC chamber is approximately 2.3 meters long, 1.5 meters wide, and 60 centimeters high. The electrode structure is about 4 meters long, 3 meters wide, and 70 centimeters high. The streamer chamber magnet (Fig. 11) produces a field of about 15 thousand gauss over a volume 2 meters in diameter and 1 meter high, and it consumes about 6 million watts of power.

The Marx generator consists of 34 stages, has sixteen 40-kV, 2,000-pF capacitors per stage, and is capable of storing 800 joules at 40 kV and of producing an output pulse in excess of 1.3 million volts, with an output capacity of about 1,000 pF. This is about twice the voltage required to drive the 2-meter streamer chamber. The characteristic impedance of the chamber is 23 ohms, so that the peak current with a 600 thousand volt pulse is about 26 thousand amps.

The momentum resolution for a 10 billion electron volt particle is expected to be 3%, while the mass resolution in multiple particle events will be as high as 1/2%. These performance estimates coincide closely with those made for a 1-meter diameter hydrogen bubble chamber, also being built at SLAC for use in photoproduction experiments. The major differences in the two devices are related to the fact that the streamer chamber, as a member of the spark chamber family, can be triggered. This will allow event selection and will permit peripheral gear, such as conventional spark chambers and counters, to be used effectively.

In a single event (Fig. 12) photographed in the two-meter streamer chamber at SLAC, an "electromagnetic interaction" occurs between an incident high energy photon and a target proton and results in a "five-prong vertex" of "strongly-interacting particles," accompanied by a "two-prong" decay via a "weak interaction." Thus all of the principal elementary particle interactions are involved in this single event.

It seems fully appropriate that the successful completion of the two-mile electron accelerator at SLAC should be accompanied by the coming of age of a new elementary particle detector--a detector particularly well suited to the exploitation of this accelerator's new and unique features.

FIGURE CAPTIONS

1. Streamer chambers, like all spark chambers, can be triggered. The passage of a charged particle is detected originally by a counter or a series of counters. Electronic logic is used to distinguish different types of events and to select those which are interesting to the experimenter. A trigger pulse is then sent to a high voltage generator whose output is used to charge a pulse-shaping network. Finally, a high voltage pulse of short duration is applied to the plates of a streamer chamber, the entire process requiring less than one millionth of a second.

2. These two streamer track photographs, each shown in two views, were obtained by F. Bulos and his collaborators at SLAC in 1965. In the second case, the high voltage pulse was intentionally delayed by 20 millionths of a second to allow the original ionization electrons left by the passage of a charged elementary particle to diffuse. In the view along the electric field and streamer axes, the streamer track appears as a series of dots about 1 millimeter in diameter. In the view perpendicular to the field, the streamers appear as a series of streaks whose length depends upon the magnitude of the high voltage pulse, as well as upon the pulse duration. In streamer production, the streamer phase is distinguished from the initial avalanche phase by the dominance of photoionization, rather than of the electron-supported ionization cascade. Photoionization causes streamers to grow symmetrically toward both the negative and the positive high voltage plates.

3. Avalanche formation, the first step in the production of streamers, was photographed by H. Raether in 1937 using a diffusion cloud chamber. The avalanche shown here originated from a single free electron at the narrow tip.

An avalanche grows longitudinally towards the positive high voltage electrode and at the same time grows radially due to diffusion of the rapidly moving electrons. The positive ions remaining after the high voltage pulse has ended serve as condensation centers for the formation of droplets in the supersaturated cloud chamber vapor.

4. This figure shows a Marx generator with four capacitive stages (C), four spark gap switches (S), and six charging resistors (R). During the charging phase, the capacitor stages are connected in parallel between the high voltage and the ground lines. When the spark gaps have fired, however, the path of least resistance is through the gaps and not through the charging resistors. The capacitors thus discharge in series to generate a pulse across the load having a magnitude equal to the sum of the high voltages on the separate capacitor stages.

5. At least three types of pulse-shaping networks can be used with a Marx generator to drive streamer chambers. Here the generator is idealized as a charged capacitor C, which discharges through an inductance L and a resistance R. In the upper figure, a second capacitor C_p is charged by the generator and is then switched onto the load R_{load} in one or two billionths of a second by means of a single spark gap S. The slower discharge of the generator is shorted to ground by means of a second spark gas S' after the fast discharge of C_p is completed. In the central figure, a transmission line replaces the capacitor C_p, and the switch S discharges the first part of the line into the second part. If the impedances of the two parts of the line are matched, a rectangular pulse of half the charging voltage results. In the final figure, a Blumlein is used to produce a pulse with the full charging voltage as well as a rectangular shape. In this case, a single spark-gap functions both as

series and shorting gaps. The Blumlein prepulse can be eliminated with a suitable "bridge" charging circuit.

6. In this side-view drawing of the experimental arrangement for the SLAC photoproduction program, a highly collimated, high energy photon beam is incident from the left and passes through a half-inch diameter hydrogen gas target in the upper of two cells containing a neon-helium gas mixture. The double-gap streamer chamber is triggered when the neutral photons produce charged particles which are detected by the counter array shown on the right of the magnet in this drawing. The locations of the Marx generator, the Blumlein pulse-shaping network, and the stereoscopic cameras are also indicated.

7. This photograph shows the SLAC two-meter streamer chamber installed in the magnet. The sheet metal radio frequency enclosure at the downstream end of the chamber has been removed for viewing. The lucite supports for the central high-voltage electrode as well as the carbon-rod terminating resistors are clearly visible. A "corona guard" encircles the central electrode to prevent breakdown at the edges. The electrode itself consists of quarter-millimeter diameter wires spaced one centimeter apart and supported on a quarter-inch thick aluminum window frame.

8. This photograph shows an "electromagnetic interaction" observed by D. Benaksas and R. Morrison in a streamer chamber experiment at Stanford. A neutral photon is incident from the left and strikes an atomic electron in the neon chamber gas to create a positron-electron "pair." The two recoil electrons of the "triplet" can be seen curving away from the vertex in a counter-clockwise direction while the positively charged positron moves clockwise in the same magnetic field.

9. In this event, photographed in the two-meter streamer chamber at SLAC, a neutral Λ^{o} was photoproduced outside of the sensitive volume. The Λ^{o} decay into a positive proton and a negative π-meson occurred within the neon-helium region of the chamber via a "weak interaction." Such decays are spontaneous and do not depend upon the nature of the chamber gas.

10. This figure is a three-dimensional, "x-ray vision" artist's conception of the SLAC photoproduction experiment. The Blumlein tapers outward and upward from the Blumlein spark gap, preserving its characteristic transmission line impedance while minimizing differences in the electric path length from the spark gap to the plates of the chamber. The streamer chamber is "terminated" in its 23-ohm characteristic impedance so that reflections of the electromagnetic traveling wave do not occur. These precautions preserve an approximately rectangular wave that reaches its peak voltage within a few billionths of a second. The Marx generator is indicated on the right of the Blumlein. The magnet windings, seven above the chamber and three below, are unbalanced to compensate for the absent top pole face. This pole face was removed to permit chamber photography through the transparent electrodes.

11. This is a photograph of the experimental arrangement for the SLAC photoproduction experiment. In this figure, the beam is incident from the right. The "elbow" section of the transmission line which couples the Blumlein to the streamer chamber is barely visible on the right, arching from the Marx generator-Blumlein oil tank to the chamber which then passes horizontally through the magnet between the visible upper and lower magnet coils. The vertical trigger-counter array, consisting in this case of 16 counters, is supported on the left-hand side of the magnet in this photograph. The trigger electronics is visible on the magnet column nearest the counters. The 400-ton

magnet, including the entire streamer chamber and drive system and the trigger counters, can be driven in and out of the photon beam along the tracks visible in the floor.

12. In this event, photographed in the 2-meter streamer chamber at SLAC, a high energy photon was incident on a proton within the half-inch diameter hydrogen gas target. Among the reaction products was a neutral particle, possibly a Λ^0, which decayed in the neon-helium region some distance beyond the vertex. This photograph, containing four background tracks, a "five-prong vertex," and a "two-prong" decay provides an excellent demonstration of the high multiple-track efficiency of streamer chambers and also of the reason why this feature is so essential in high energy experiments. An extrapolation of the observed tracks into the target region allows a precise reconstruction of this portion of the event history.

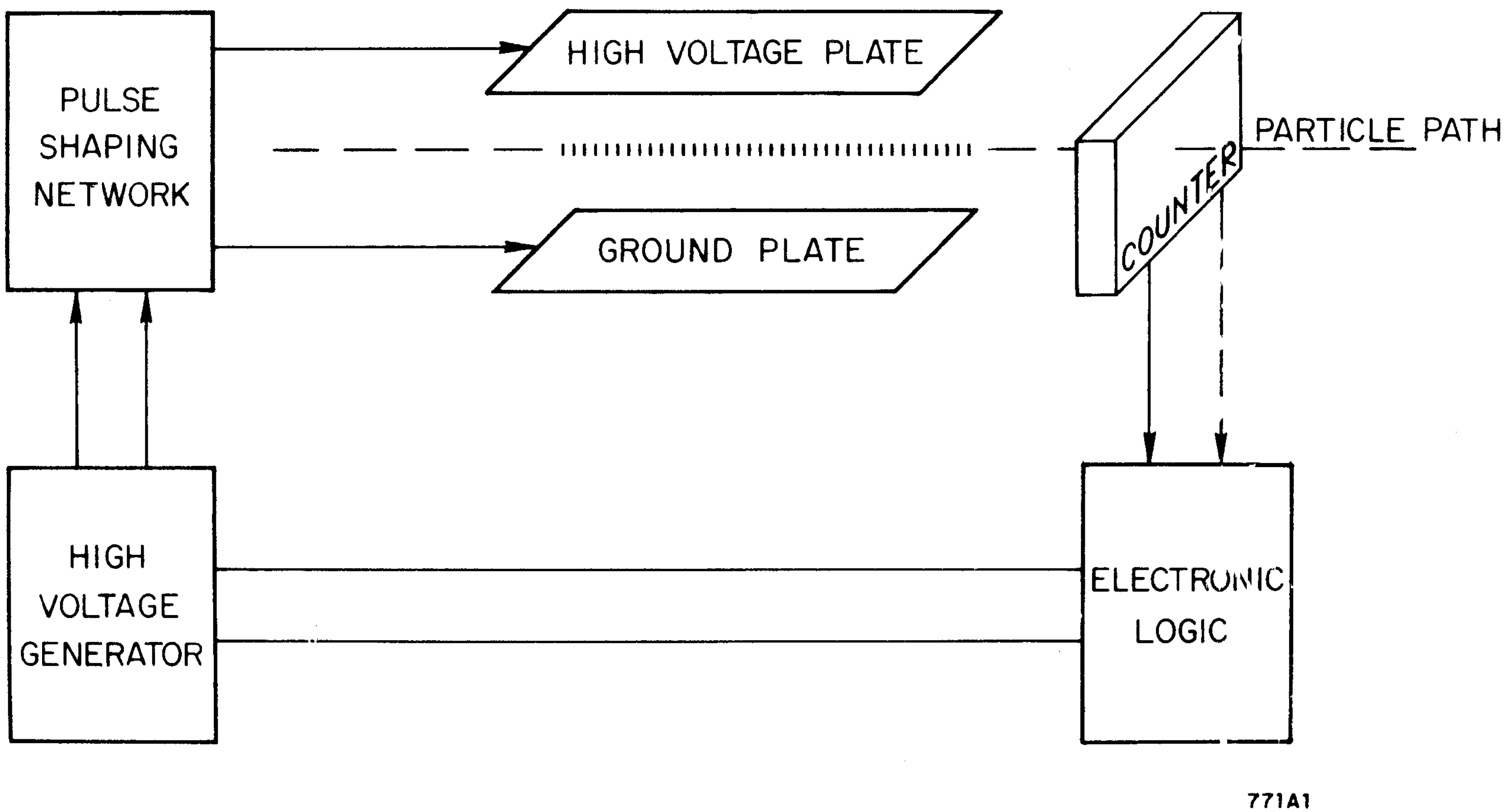
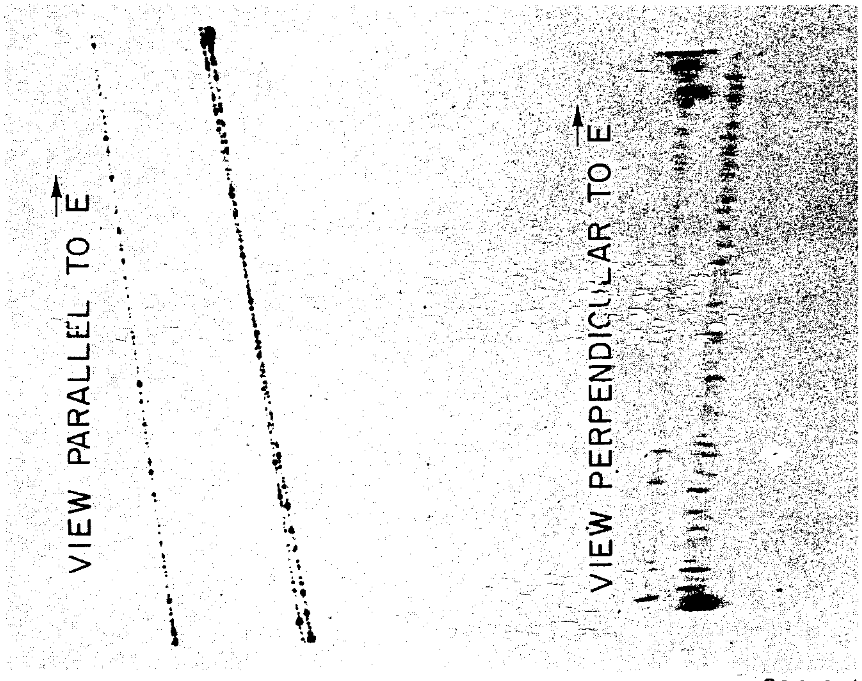
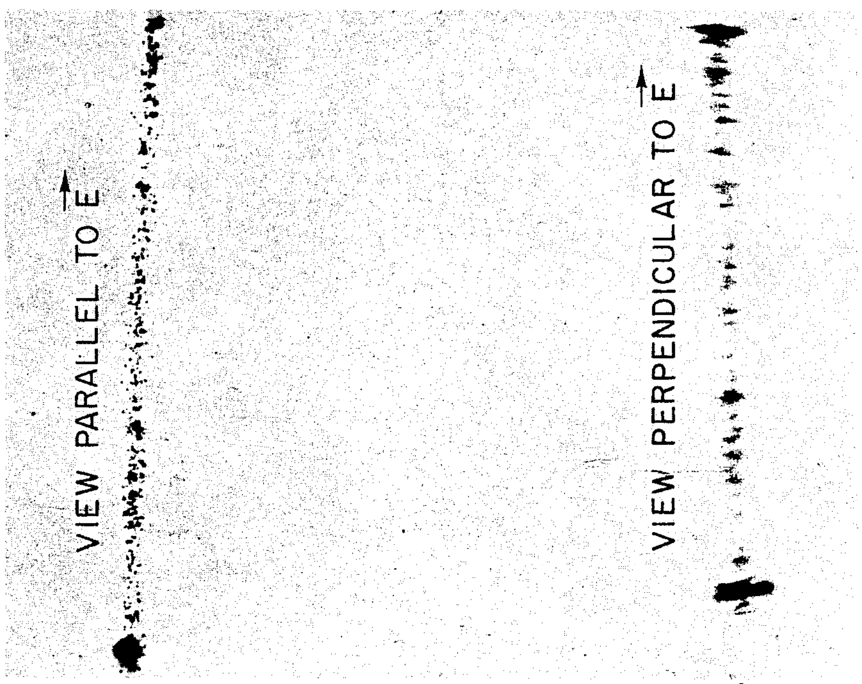

PULSE
SHAPING
NETWORK
HIGH VOLTAGE PLATE
GROUND PLATE
COUNTER
PARTICLE PATH
HIGH
VOLTAGE
GENERATOR
ELECTRONIC
LOGIC
771A1

FIG. 1



285-8-A

FIG. 2a



285-9-A

FIG. 2b

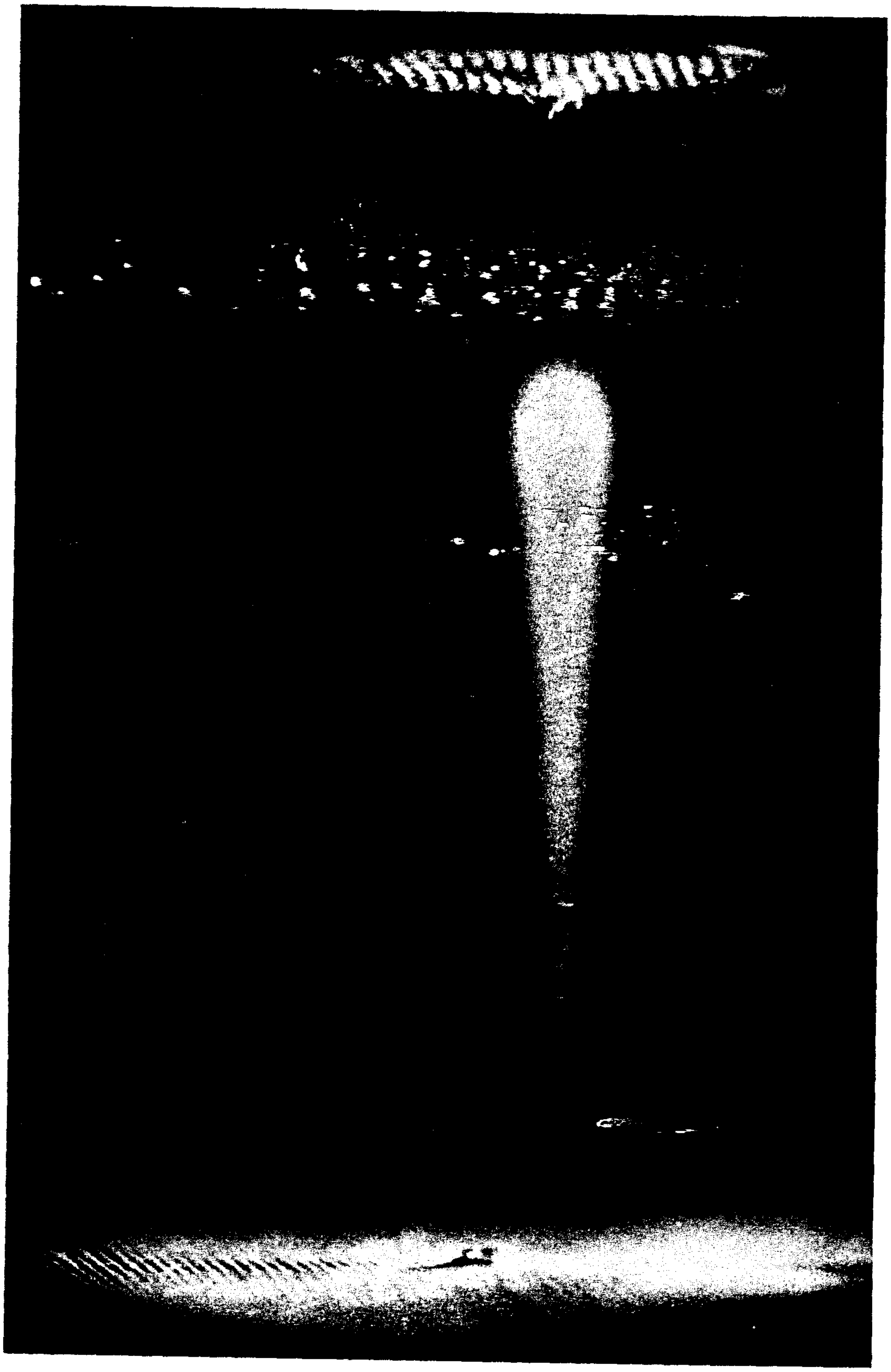


FIG. 3

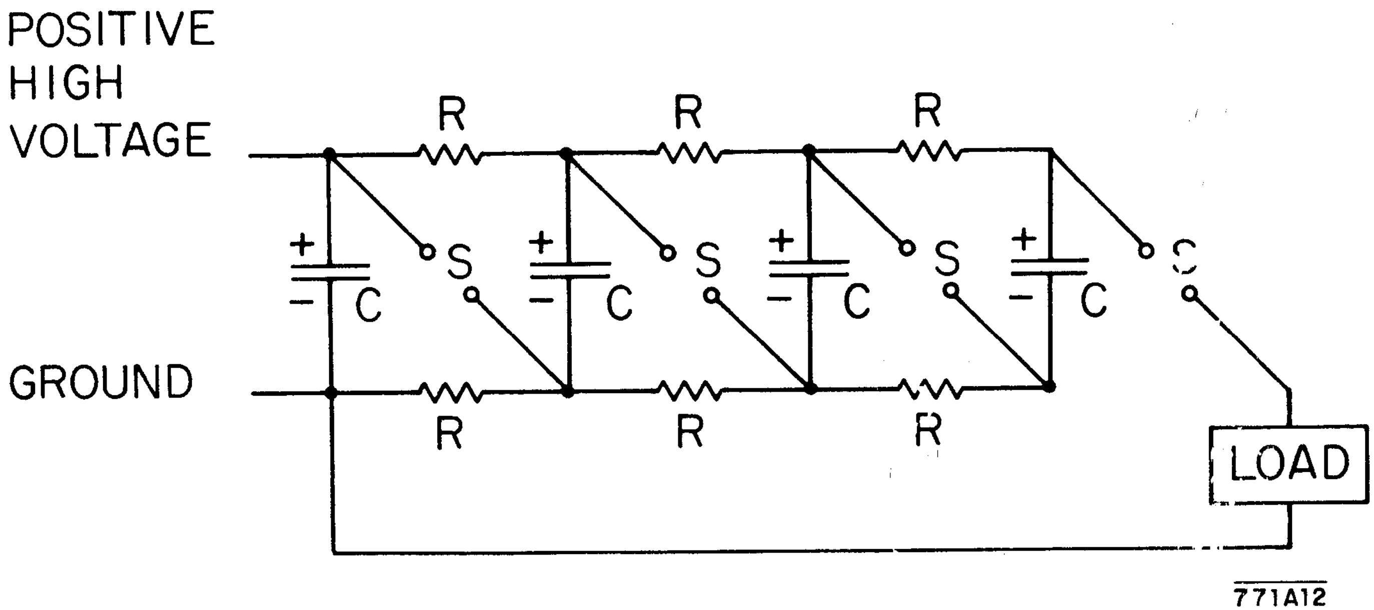
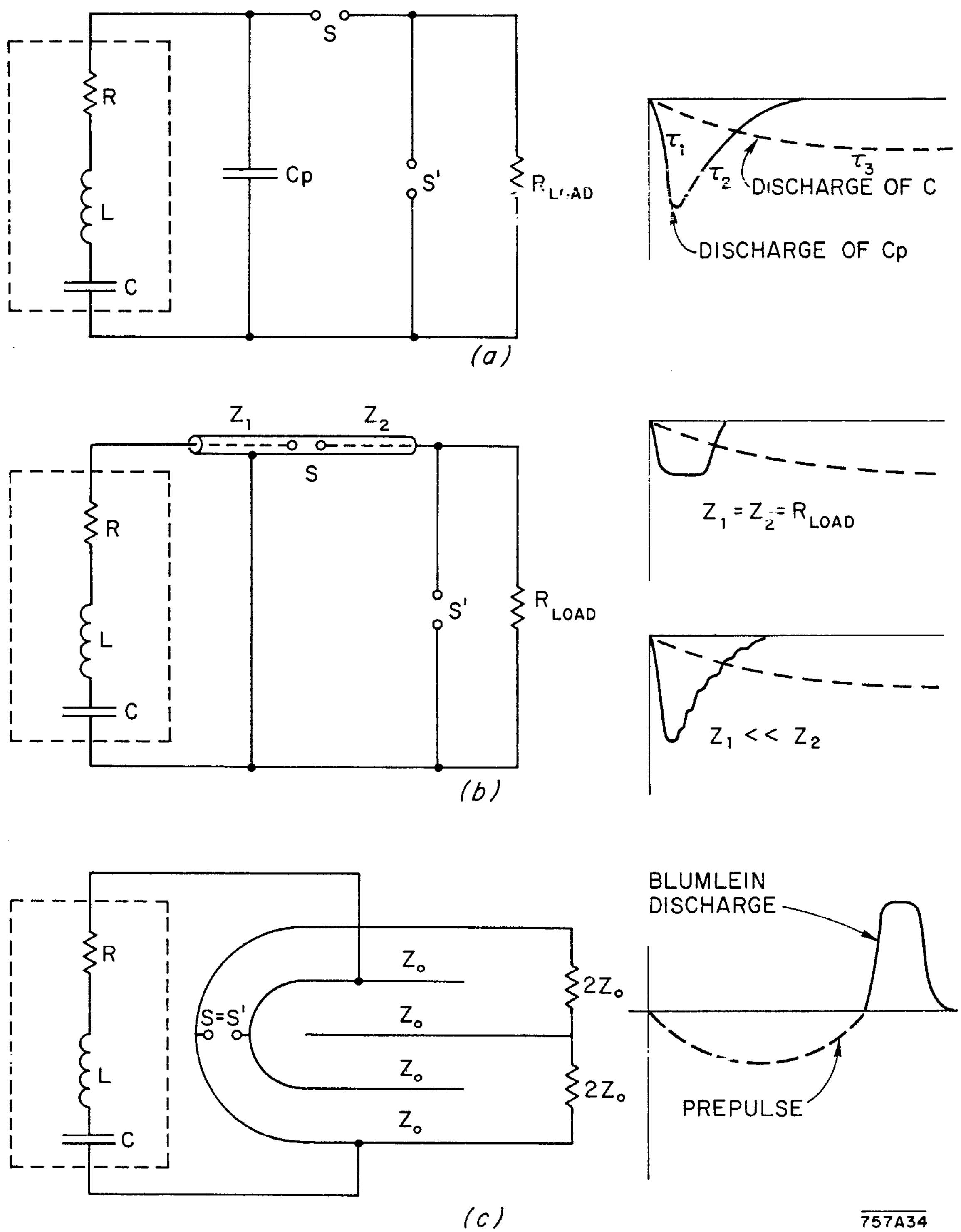


FIG. 4



S
R
Cp
S'
L
C
DISCHARGE OF C
DISCHARGE OF Cp
(a)
Z1
Z2
S
R
S'
R LOAD
L
C
Z1 = Z2 = R LOAD
Z1 << Z2
(b)
BLUMLEIN
DISCHARGE
R
Zo
2Zo
S=S'
L
C
PREPULSE
(c)
757A34

FIG. 5

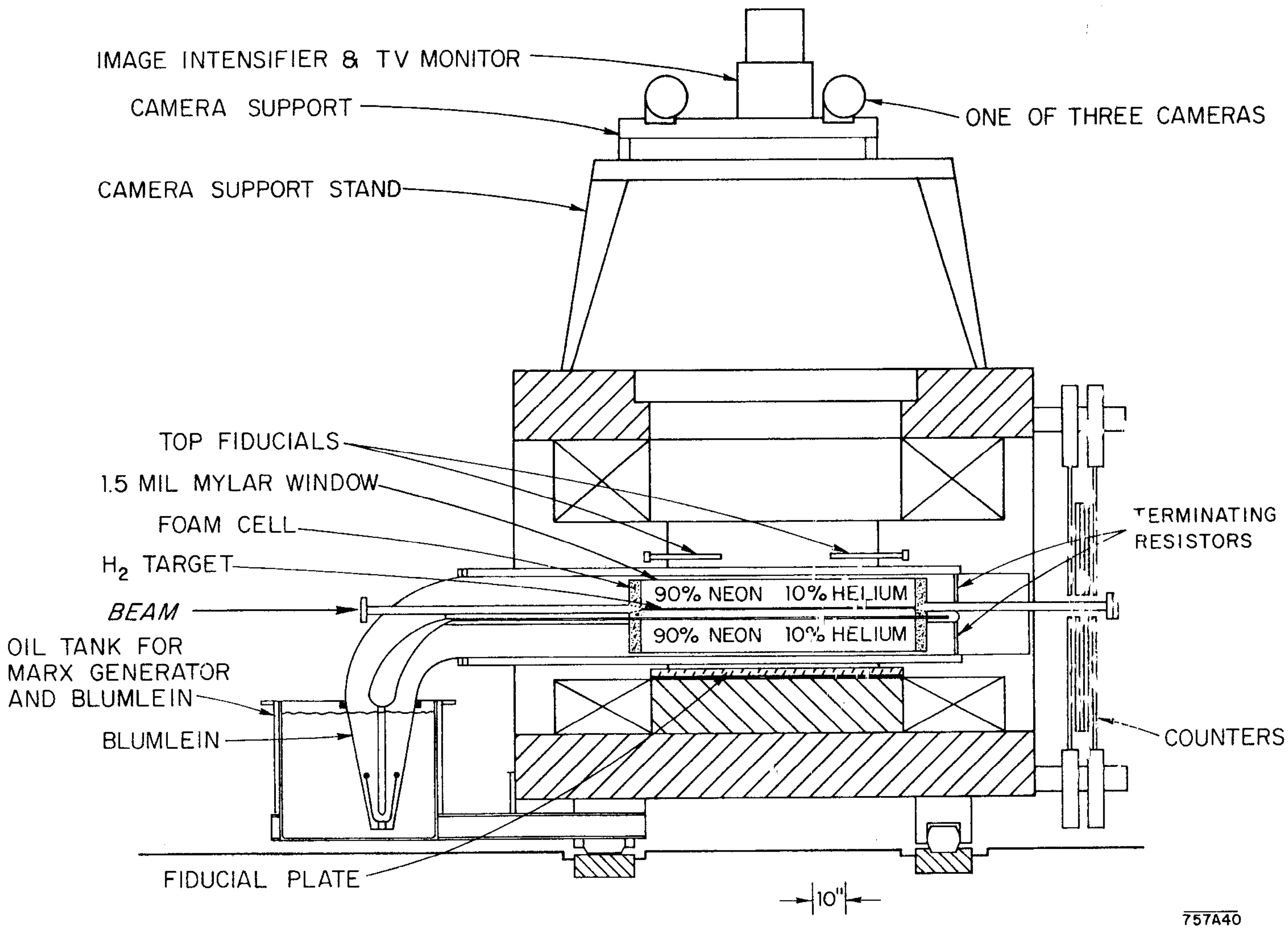
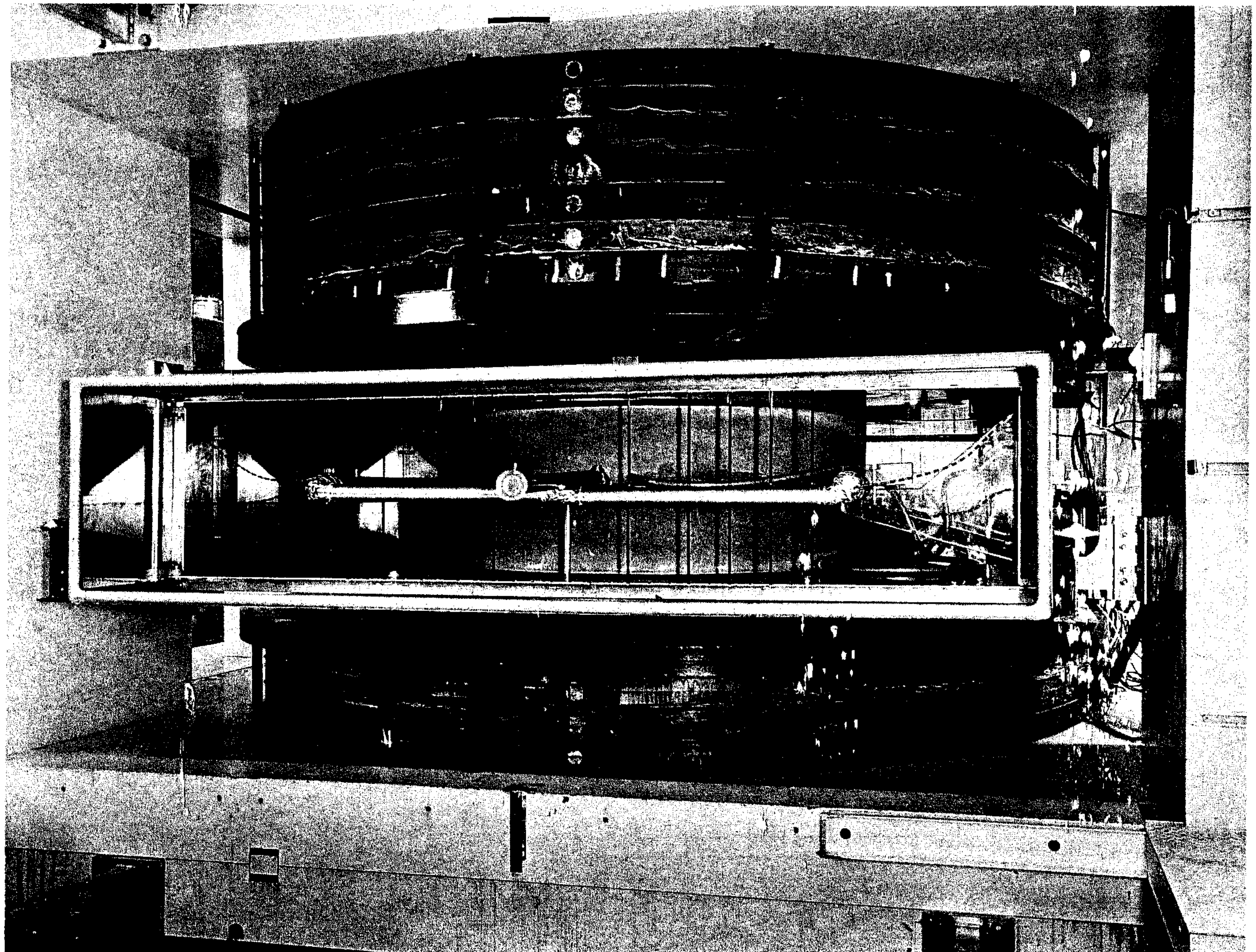


IMAGE INTENSIFIER & TV MONITOR
CAMERA SUPPORT
ONE OF THREE CAMERAS
CAMERA SUPPORT STAND
TOP FIDUCIALS
1.5 MIL MYLAR WINDOW
FOAM CELL
H2 TARGET
BEAM
OIL TANK FOR MARX GENERATOR AND BLUMLEIN
BLUMLEIN
TERMINATING RESISTORS
90% NEON 10% HELIUM
90% NEON 10% HELIUM
COUNTERS
FIDUCIAL PLATE
10"
757A40

FIG. 6



757A51

FIG. 7

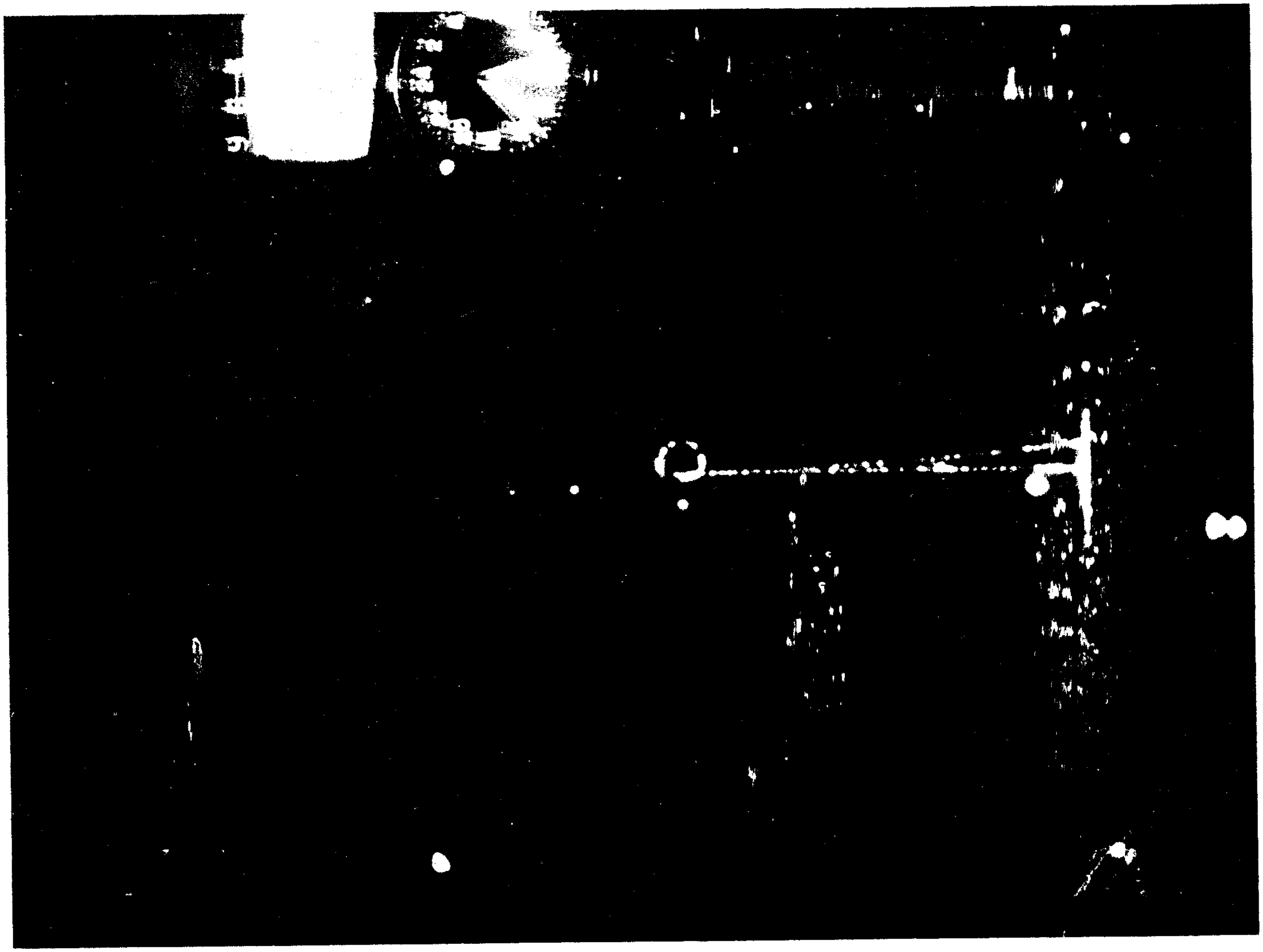
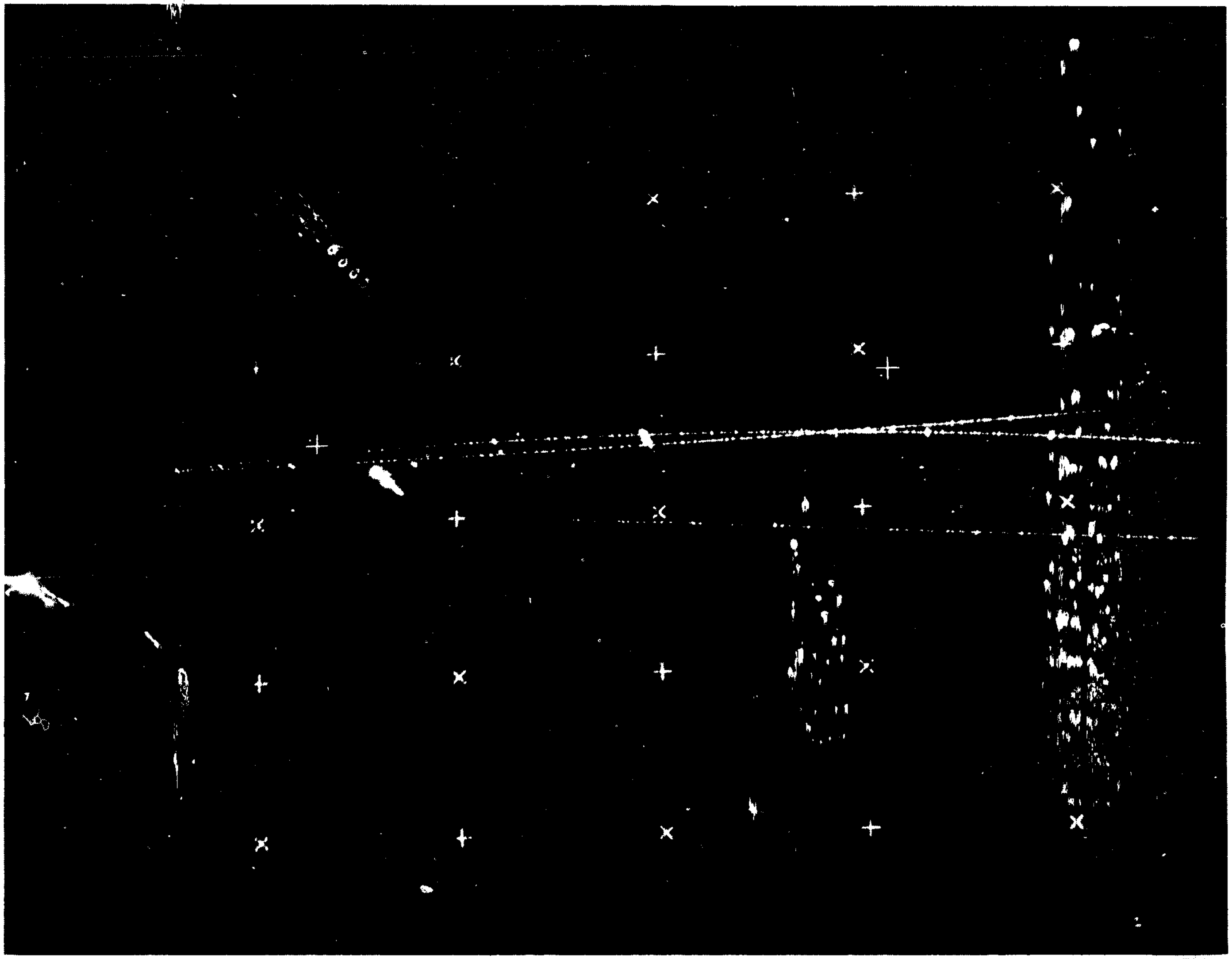


FIG. 8



757A53

FIG. 9

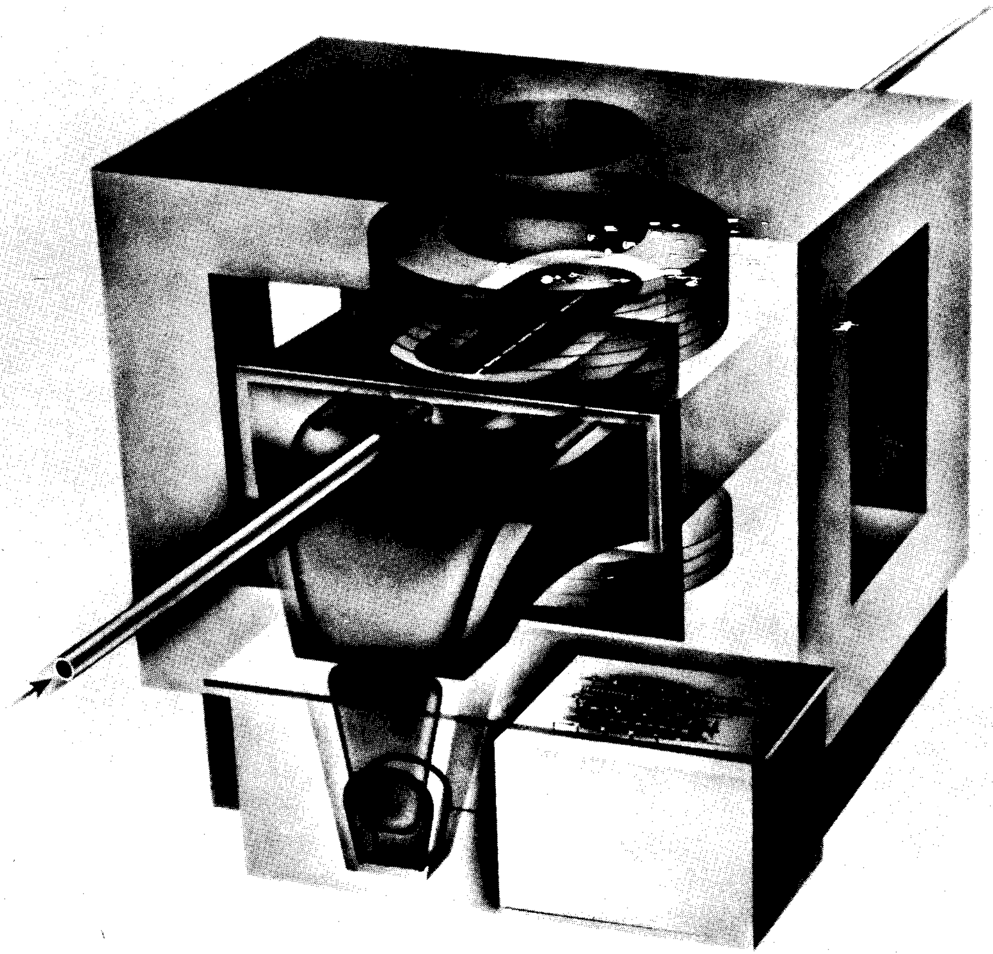
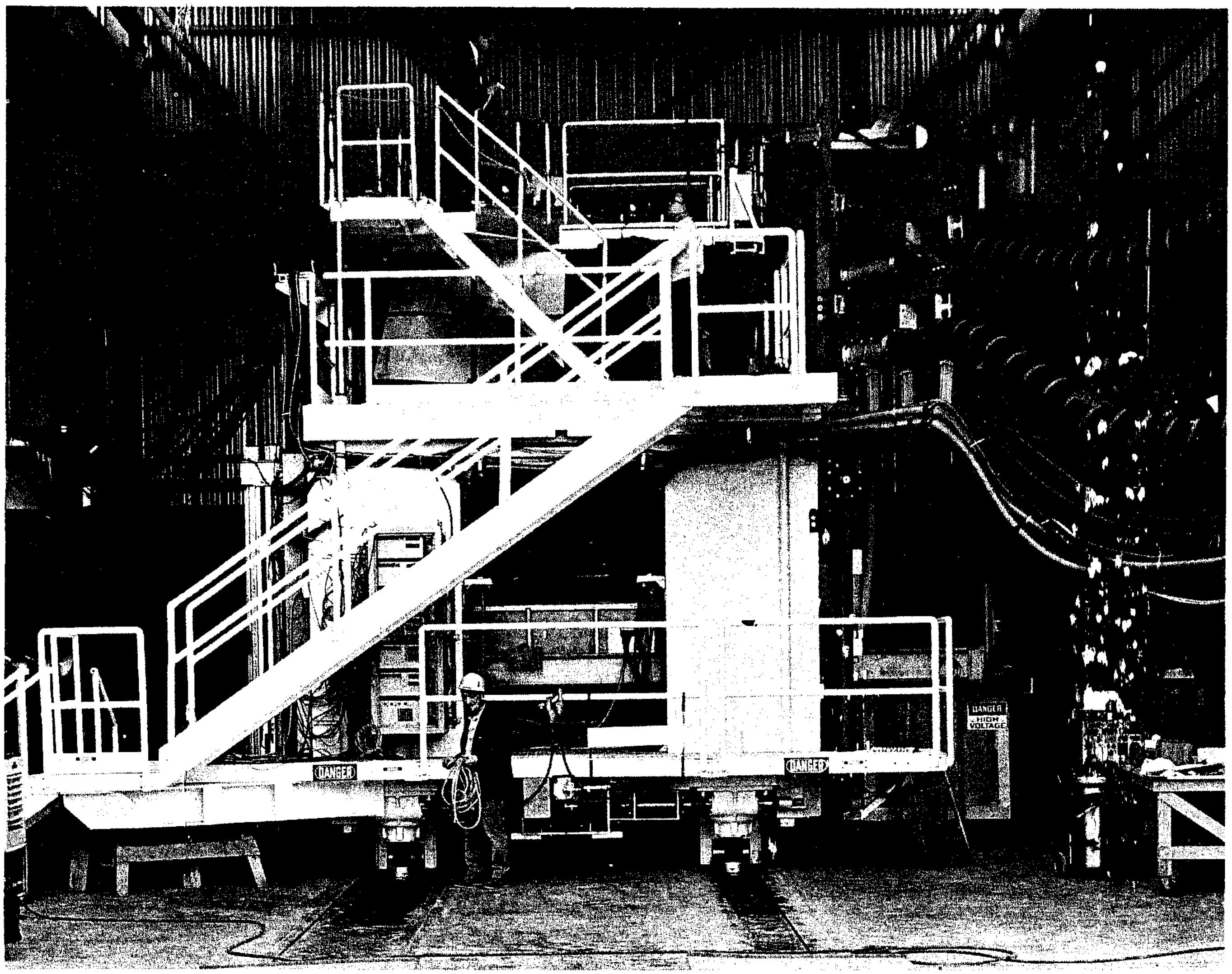


FIG. 10



757A50

FIG. 11

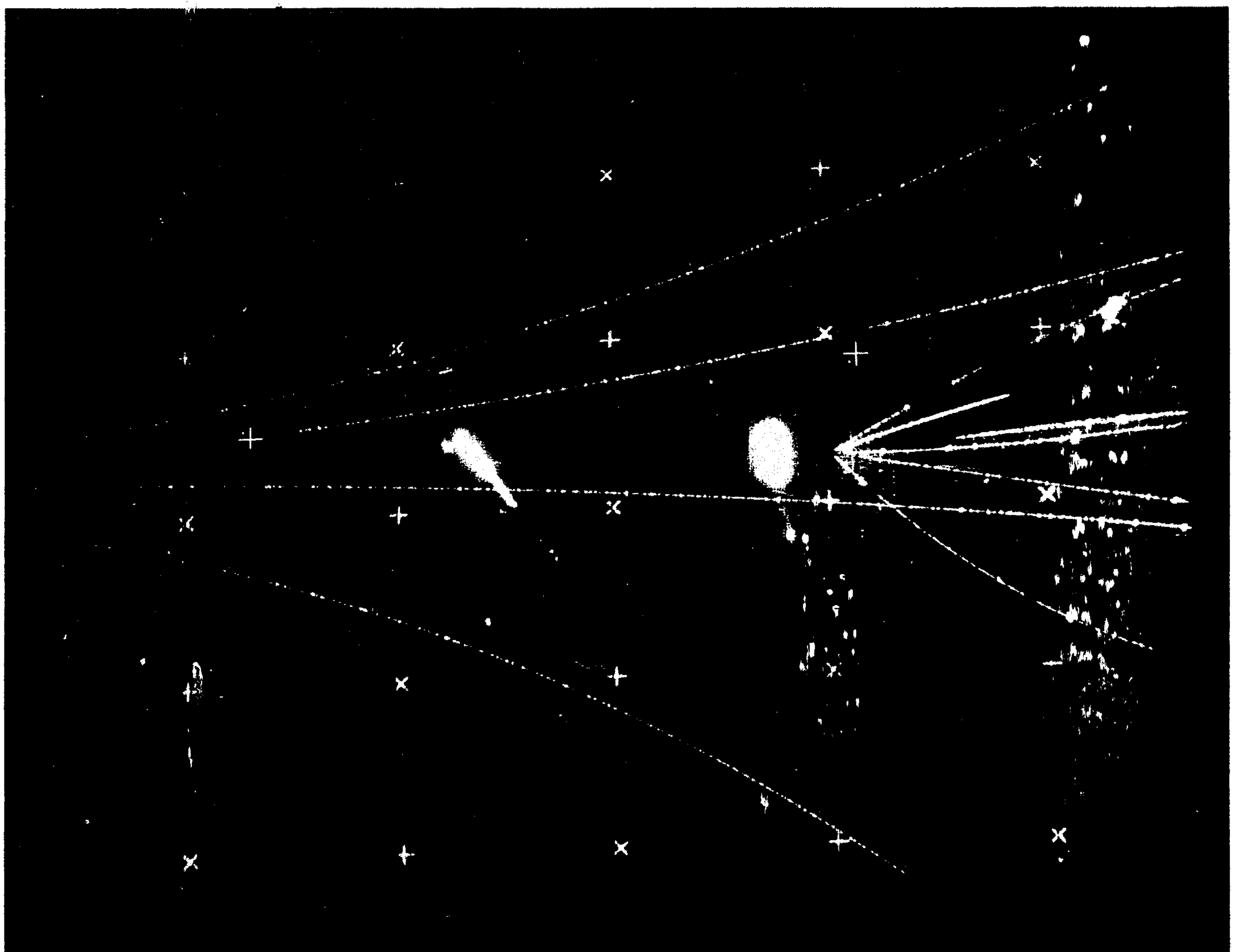

757A54

FIG. 12