Title

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Publication Date

1952-03-01

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Berkeley, California

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March 14, 1952

Berkeley, California

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Introduction

The ion source to be described in this paper was designed specifically for use in the 4 Mev Berkeley Electrostatic Generator[1,2]. The principal task of this machine is as an injector for the 32 Mev proton linear accelerator[3,4]. This use places somewhat different requirements on source parameters than is usual in Van de Graaff practice. The major difference stems from the relatively low duty cycle of the linear accelerator which places a premium on current delivered during the machine pulse. In order to have large current in the accelerating period without excessive average drain on the electrostatic machine, the source must be readily modulated. The spot size must be small enough so that the entire beam can be put into an area small compared with the 1/2 inch opening in the first drift tube. Reliability is an important consideration since the overall accelerator is really two more or less complicated machines operated in series, and outage for either outage for both.

The original ion source used in the Berkeley machine was a modified Zinn design[5], which could be operated either continuously or pulsed. Pulsed operation required large arc currents which placed severe operating conditions on the oxide filament. The filament life under pulsed operation was short, the pulsed power requirements were large, and at best only a factor of ten in peak current over continuous current could

be obtained. It was apparent that while the Zinn source would provide a satisfactory continuous beam, it was not suited for our mode of operation. Consequently, work was started in 1948 to develop a source specifically for pulsed operation. The design to be described here resulted from this work.

The type of gaseous discharge device generally known as a Penning or Phillips ion gauge[6] was chosen as the basis for the design because it has geometrical forms that will produce a stable discharge. Its advantages, aside from simplicity, are low pressure operation due to the multiple transversals of the gas by the ionizing electrons, high efficiency, since nearly one-half of the total arc current is carried by ions, no filament, and small physical size. Axial extraction of the ions was chosen as the simplest way to bring out the beam.

Source Geometry

A scale drawing of the ion source as used during the experimental investigation is shown in Fig. 1. The cylindrical anode is mounted axially between the rear and front cathodes, supported on a lava insulator. The entire assembly, including the probe which is also mounted on a lava insulator, is slipped piece by piece into the stainless steel arc chamber from the front and locked in place by a threaded ring. This technique eliminates entirely the use of gaskets in sealing the arc chamber volume. The front cathode is machined to form a hollow cone of 90° included angle. The apex of the cone enters the arc chamber with a diameter of .030 inch to .040 inch to form the exit aperture. The probe is also machined to form a 90° cone and is placed concentric with the hollow cone of the cathode and spaced therefrom .060 inch to .080 inch.

The entrance aperture in the probe is 1/8 inch. With this 90° geometry, and probe voltages in the range of 10 to 15 kv, an extremely strong focusing action is experienced by the beam near the exit aperture. Under these conditions the probe current is essentially zero. With less acute cone angles, an appreciable fraction of the beam would strike the probe, unless the probe aperture is changed.

The entire arc chamber is centered in a coil to provide a magnetic field adjustable over the range of 500 to 1000 gauss. By keeping the arc chamber volume small, the required field is produced with a d.c. power of 100 watts in the coil.

Mechanism of the Discharge

Although many are familiar with the basic mechanism of the Penning discharge, it will be reviewed here briefly as a point of departure for the discussion to follow. Consider the geometry of Fig. 1 with a hydrogen pressure in the arc chamber of the order of 20 μ, a magnetic field in the range of a few hundred gauss, and a positive potential in the range of a few hundred volts existing between the anode and cathodes.

If an electron is released from either cathode it will be accelerated into the anode, its radial motion constrained by the magnetic field. The electron will coast through the field free region in the anode, losing some energy to the gas and, leave the anode at the other end with somewhat less energy than it gained in the initial acceleration. There it will be reflected by the electric field, re-enter the anode and continue its axial oscillation. In the process it will sooner or later make several ion pairs, losing energy in the process. Since the energy lost in ionizing is of the order of 35 volts, and the initial energy of

the electron is several hundred volts, approximately ten ions will appear inside the anode before the initial electron is below ionization energies. These ions are also constrained by the field, their principle motion therefore being axial. Eventually, they will come to one end of the anode where they will be accelerated into the corresponding cathode.

For hydrogen ions of a few hundred volts, incident on an aluminum oxide surface has a finite probability of releasing a secondary electron. Such electrons will be accelerated into the anode region to continue the ionizing process. Although good data on the magnitude of the proton to secondary electron ratio (N) for aluminum oxide is lacking, it seems reasonable to assume that it will lie between 5 and 10 in our case. If more ions than N are produced by the first electron, the discharge will increase in intensity until limited by other mechanisms. This limit is normally set by an external series resistance in the anode circuit, which causes the anode potential to fall as the discharge increases. Under this condition an equilibrium between the number of secondard electrons produced per ion and the number of ions produced per fast electron will be reached.

As the discharge builds up, a plasma column forms which extends through the anode, terminating in a cathode sheath at each end. An approximation of the dimensions of this sheath can be obtained by applying the space charge law for positive ions emitted from the plasma surface to the cathode, neglecting the small space charge neutralizing effect of the ionizing electrons which are being reflected in the plasma cathode interspace. If we take the plasma diameter as 3/16 inch, the ion current as 0.2 amperes, and the arc drop as 300 volts, we calculate a spacing of about .01 cm to be required to satisfy the space charge conditions.

The presence of the oscillating electrons increases the spacing slightly.

Current Balance

It is an important characteristic of this discharge that the ratio of ion to electron current is not of the order of $\sqrt{\frac{m_p}{m_e}}$, as in the Zinn and similar sources, but rather the current is nearly equally divided between positive ion current to the cathodes (I_p), and the current of slow electrons (I_e) made in the process of producing the ions together with the current (I_i) of degraded ionizing electrons which eventually reach the anode. Since one slow electron is made for each positive ion, these two components must be equal. The ionizing electron current is equal to the positive ion current incident on the cathodes divided by N. The total current is $I_p + I_e + I_i$ with $I_i = I_p/N$, and $I_p = I_e$. The positive ion current to electron current ration is then $\frac{1}{1 - \frac{1}{N}}$. If at a typical anode voltage of ~300 volts, N is assumed equal to 5, the positive ion to electron current ration is 1/1.2.

For the source shown in Fig. 1, typical values of pulsed arc current used were in the range of 1 to 2 amperes. With two amperes, we have approximately 800 ma of ions incident on both cathodes or 400 ma per cathode. The anode collimates the discharge to a diameter of 3/16 inch. The current to be expected through the exit hole obviously is $I_p \cdot A/a$. With an exit hole diameter of .030 in., we have an area ratio of $1875^2/.030^2 = 3.9 \times 10^{-3}$. If the current to the front cathode is 400 ma, the exit beam will be $4 \times 10^2 \times 3.9 \times 10^{-3} = 1.55$ ma, which is in reasonable agreement with the saturation beam as shown in Fig. 2.

It was found experimentally that the proton to molecular ion ratio in the beam improved with increasing arc current. The best operation

in this respect is therefore obtained by running as large an anode current as practicable, and using the probe voltage to control the beam current. The beam current varies from essentially zero to maximum with a variation of about ten kilovolts on the probe.

Discharge Oscillations

Two distinct types of oscillations were observed in the arc voltage and current. One of these is of a relaxation character, which occurs only with excessively high magnetic fields. This apparently comes about when the magnetic field is such as to restrict the radial drain of slow electrons from the plasma to the anode. Under this condition, the plasma potential falls away from the anode, and the current decreases to zero for a period of the order of several microseconds, whereupon the arc will re-strike. This form of oscillation is absent until the magnetic field reaches a certain critical value and its frequency is roughly porportioned to the excess field. The magnetic field at which it occurs is determined by the length of the anode. It was found in experiments with various anode lengths that the critical field which produced this oscillation was in direct ratio to anode length for geometries and conditions which are otherwise the same.

The second type of oscillation encountered was one that produced essentially sinusoidal modulation of the current at radio frequencies. This oscillation was more or less random in occurrence and invariably reduced the beam current when present. It was found possible to eliminate it completely by a series of R-C network connected between anode and cathode as long as the lead length was kept small and non-inductive resistors were used. By keeping the magnetic field below the critical

point where relaxation is encountered, and using the rf suppressor, completely clean current pulses are produced.

The lower limit on magnetic field is set by the requirement of providing sufficient collimation to prevent the premature loss of the ionizing electrons to the anode. The range of stable operation for the geometry shown was from about 500 to 1000 gauss. With the shortest (1/2 in.) anode used in the experiments on relaxation oscillations, the lower limit was about 400 gauss; high field relaxation came in at about 500 gauss. The band of stable operation with respect to variation of magnetic field is proportional to the length of the anode.

Arc Chamber Materials

With the exception of the cathodes, the materials used in construction of the source are not critical. The arc chamber and anode must be non-magnetic. Stainless steel was chosen for its freedom from corrosion. The anode insulator can be of any non-porous ceramic. Care must be taken to keep organic materials out of the chamber which might vaporize and then be broken up by the discharge, to deposit carbon on the cathodes.

The choice of cathode material is very important since it determines the running voltage of the discharge and hence the power required to produce a given anode current. The commonly available metals fall into two distinct voltage ranges when used as cathodes for a P.I.G. discharge. Metals which have been investigated[7] are listed in Table 1. It is seen that there is about one order of magnitude higher arc voltage for the second group than the first.

In our work, 2S aluminum, beryllium, magnesium, and dural were investigated. The first two are entirely satisfactory, but magnesium

and dural are not.

The low discharge voltage metals are characterized by having oxides with extremely high melting and boiling points, as well as high heats of formation. This oxide film apparently plays a key role in that it reduces the voltage required to have a given secondary ratio, and hence the equilibrium discharge voltage. After long operation, the film will be removed even from beryllium or aluminum. If operation is continued during the time the last of the oxide is being removed, the arc voltage will gradually climb until it is running in the same range as the Group II metals. By then admitting oxygen, the layer can be restored and operation will return to normal. The first effects of loss of oxide with the source described occur after about 100 hours of operation. Therefore, a side tube containing silver oxide, which can bedecomposed by heating, is provided. The oxidizing procedure used has been to run the source on O_2 at normal pressures for a period of about 30 minutes as needed.

It is believed that the effect of this aluminum oxide surface is as follows. Positive ions from the arc fall to this cathode surface charging it positively. The resulting electric field across the aluminum oxide surface is sufficient to pull electrons through the oxide layer into the discharge. Guntherschulze (Zeit. fur Phys. 106, 662 (1937)) has studied this phenomenon of "spray emission" in some detail, and has measured a maximum yield of 4×10^6 V/cm independent of the oxide thickness. He finds also, that the layer thickness can be increased to the point where there is no measurable voltage drop from the discharge to the oxide surface, and no visible dark space.

Although magnesium oxide should meet the stability requirements, its oxide film appears to craze under ion bombardment, which exposes the bare metal to the impinging ions. This results in sputtering of the

magnesium and rapid wear of the cathodes and the edges of the ion exit hole.

In a properly oxidized source, the rate of cathode wear on aluminum or beryllium due to the discharge is negligible. One front cathode was removed after approximately 2500 hours of operation. It had a depression of about .001 in. in depth, and a diameter equal to that of the plasma. The ion exit hole had increased in diameter by about .005 in. during the period.

Focusing System

A two electrostatic lens system following the probe is used to provide focusing and initial acceleration of the beam. When operating in the Van de Graaff generator the probe voltage is set between 5 and 15 kv to determine the beam current. The focus electrode is operated in the neighborhood of 10 kv, with the accelerating electrode set at about 50 kv. The focusing electrode to probe system is a relatively weak lens, since in normal operation the voltage ratio is not large. The strong lens is between the focus and accelerating electrode. This arrangement permits beam amplitude control through variation of the probe voltage, without serious defocusing, since only the focal length of the weak lens is varied. If the focusing electrode were omitted, the overall lens strength would vary rapidly with probe voltage, and it would be difficult to maintain a focus over a wide range of beam current.

Approximations to the focusing action of the accelerating tube were made and it was concluded that a beam injected with an angular divergence of about $.5^{\circ}$ would produce a cross over or focus at the exit end of the tube. The three electrode system can provide a beam with

from several degrees of divergence to several degrees of convergence at the point of injection to the tube. This range is more than adequate to provide a good focus over a range of machine energy from 1 Mev to 4 Mev. The theoretical angular divergence of the 4 Mev beam is .05°.

In the initial installation provision was made for remotely controlled motors which could move the focusing electrode in a plane normal to the beam. This provided gross angular control of the beam to compensate for possible mis-alignment of the source with respect to the accelerating tube. The alignment problem proved not serious and in a later modification the motors were removed.

Gas Flow and Differential Pumping System

The supply of hydrogen for the source is a pressure tight steel bottle mounted inside the high potential shell. Hydrogen gas from the bottle is passed through a palladium tube which is provided with an electrical heater. Control of the palladium temperature is accomplished through the machine control system. The palladium leak serves the dual purpose of controlling the rate of flow of hydrogen and preventing the possible entry of other contaminating gases into the arc chamber.

The neutral gas flow from this source is quite low, since the arc pressure is relatively low and the exit hole small. For hydrogen at a chamber pressure of 25 microns, the flow is 5.5 micron liters per second, or 26 cc S.T.P. per hour. A differential pumping system existed for the originally installed Zinn type source. It consisted of an oil diffusion pump and a mechanical pump which exhausted into the hydrogen supply bottle. This system was used, but the usual low speed gas baffle between source and tube was eliminated. By opening up as much area as

possible from the pump to the tube, the pressure in the region where the ion have low energy and hence are most susceptible to scattering, could be reduced drastically. This scheme worked well in initial tests and permitted a very finely focused beam to be produced at the output of the machine. Experience showed that over long periods of time the small contamination of pump oil resulting from the use of this system was damaging to the tube and consequently the pump was removed. Without this system the best focus at ground is a spot about .10 in. in diameter.

Electronics

As previously mentioned, the source is operated in a pulsed manner, its pulses produced in synchronism with the linear accelerator. A hard tube pulser with 2 type 811 transmitting tubes in parallel was chosen because of the essentially constant current characteristics of these tubes, combined with extremely small bias requirements for cutoff. The large plate resistance of these tubes permits changes in anode voltage to occur without appreciable effect on the anode current. The 811 tubes are connected as a series switch between the anode power supply and the anode. The power supply is run between 1000 and 1500 volts. Therefore, when the grids of the 811 tubes are pulsed positive, the anode voltage will rise rapidly, as high as necessary to insure fast starting of the source, then fall to the running value as the discharge comes into equilibrium. With this over-voltage starting, the beam is up to full current within 5 microseconds after the start of the pulse.

Since the 811 tubes must float at anode potential, a transformer is used to transfer the driving square wave from a single shot multi-

vibrator and cathode follower to their grids. The arc pulse length is set to about 450 microseconds by the multivibrator time constants.

The initiating signal for the beam pulse must come from ground potential and trigger the pulser which is at 4 Mv. This is accomplished by pulsing a Sylvania type R1130B glow tube, located inside the ground end of one of the textolite supports for the high voltage terminal. Inside the high potential end of the textolite tube, a 931 A photomultiplier followed by a small preamplifier receives the light signal and generates the proper pulse to trigger the pulser. The light pulse is made 100 microseconds long. An integrating circuit with a time constant of 50 microseconds is used between the preamplifier and pulser to prevent random triggering on light from small sparks which seem to occur more or less frequently in the insulating structure of the machine. A block diagram of the electronics is given in Fig. 3.

D.C. Supplies

All power for the source when installed in the high voltage shell comes from a 5 kw 400 cycle permanent magnet generator which is driven from the upper belt pully. The d.c. supplies required for the anode, probe, focus and accelerating voltage use selenium rectifiers to eliminate the servicing problems inherent in vacuumtube circuits. With the exception of the anode supply, all are conventional half wave voltage multiplier circuits, using two stages in the case of probe and focus supplies and four stages for the accelerating voltage. The anode supply is a half wave circuit variable remotely from 0 to 2000 volts. The probe and focus supplies can be varied from 0 to 20,000 volts, and the accelerating supply from 0 to 60,000 volts. The use of 400 cycle

power permits large savings in transformer and filter capacitor size. These power supplies have proven extremely reliable in operation.

Performance

The source described was installed in the Van de Graaff generator in February, 1948, and has been in use since that date. It has operated for many thousands of hours, with no maintenance other than that of a routine character. If care is taken to keep the gas supply line and arc chamber free of organic vapors, and if oxygen is supplied at proper intervals, the cathode life is indefinitely long. The margin of stability, with respect to small variation of gas pressure, magnetic field, or anode power supply voltage, is such that the source can be turned on and left without attention for many hours. The beam composition was measured during the development program and after installation in the machine. A typical set of operating data taken from the experimental program are:

Peak are current	2 a
Starting anode volts	600 v
Running anode volts	300 v
Probe	15 kv
Focus	10 kv
Accel.	55 kv
H^+ peak current	1.5 ma
H_2^+ peak current	.9 ma
H_3^+ peak current	.3 ma

In normal use, the pulse length is 450 microseconds, with a repe-

tition rate of 15 cps, giving a duty cycle of 1/150. For some experiments using the Van de Graaff beam directly, the duty cycle has been raised to as high as 1/30. Under these conditions, an average beam of 50 μamp of 4 Mev protons was obtained.

The energy spread of the beam has not been measured, but should result principally from the discharging of the high potential electrode during the beam pulse. The capacity of the shell to ground is about 200 $\mu\mu$f. Taking the total accelerated beam as 3 ma for 450 microseconds, the potential of the shell, and hence the beam energy, should decrease about 7 kv during a pulse. As an injector for the linear accelerator, this change in energy is negligible.

Acknowledgments

The authors wish to take this opportunity to express appreciation to the members of the accelerator crew who aided in various phases of the work, Mr. Walter Sessions of the Electronics Group who designed the control circuits and d.c. supplies, and to Dr. Luis Alvarez and Dr. Hugh Bradner whose enthusiastic support contributed greatly to the success of the source development. This work was done under the auspices of the A.E.C.

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TABLE 1

Table of Cathode Metals vs Arc Voltage

Group I		
	Aluminum	350
	Be	280
	Mg*	400
Group II		
	Nickel	3600 v
	Zinc	3600
	Cu + 3% Be	3600
	Brass	2800
	Monel	2800
	Copper	2300
	Carbon	2300
	Molybdenum	1800

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ref: Backus UCRL BP27

* the authors

Figures

1. Cross section of source showing magnet, arc chamber, probe, focus, accel. electrodes.
2. Probe volts vs Beam.
3. Block diagram of associated electronics.

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3/17/52 bw

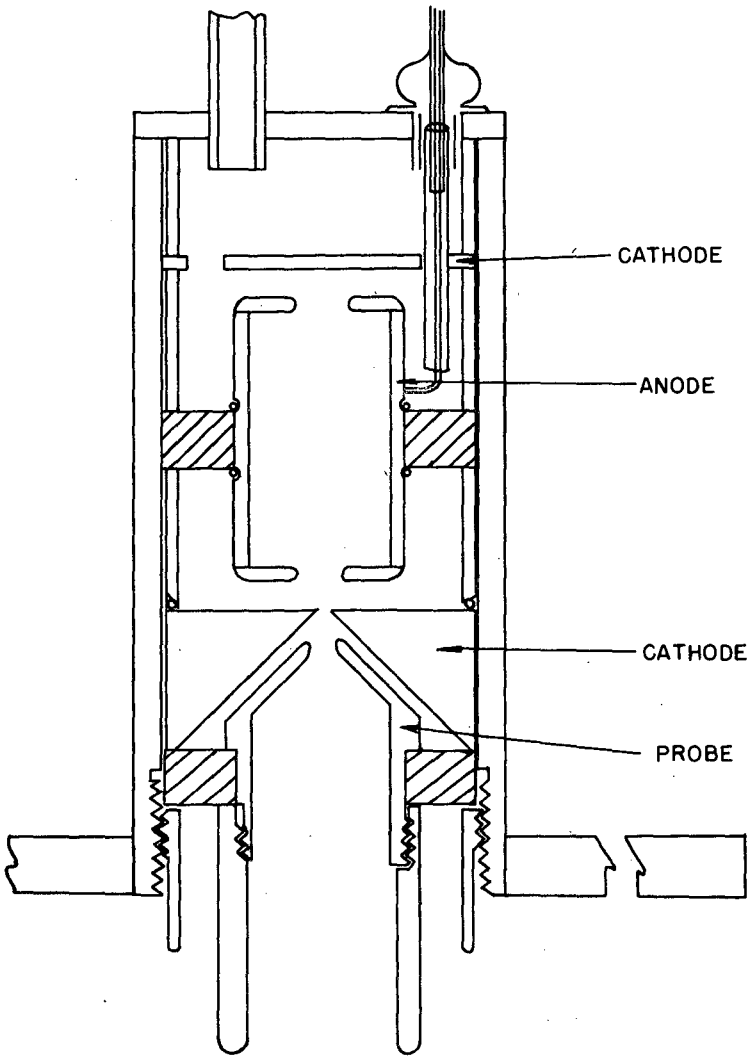

FIG. 1

PIG ION SOURCE

MU3409

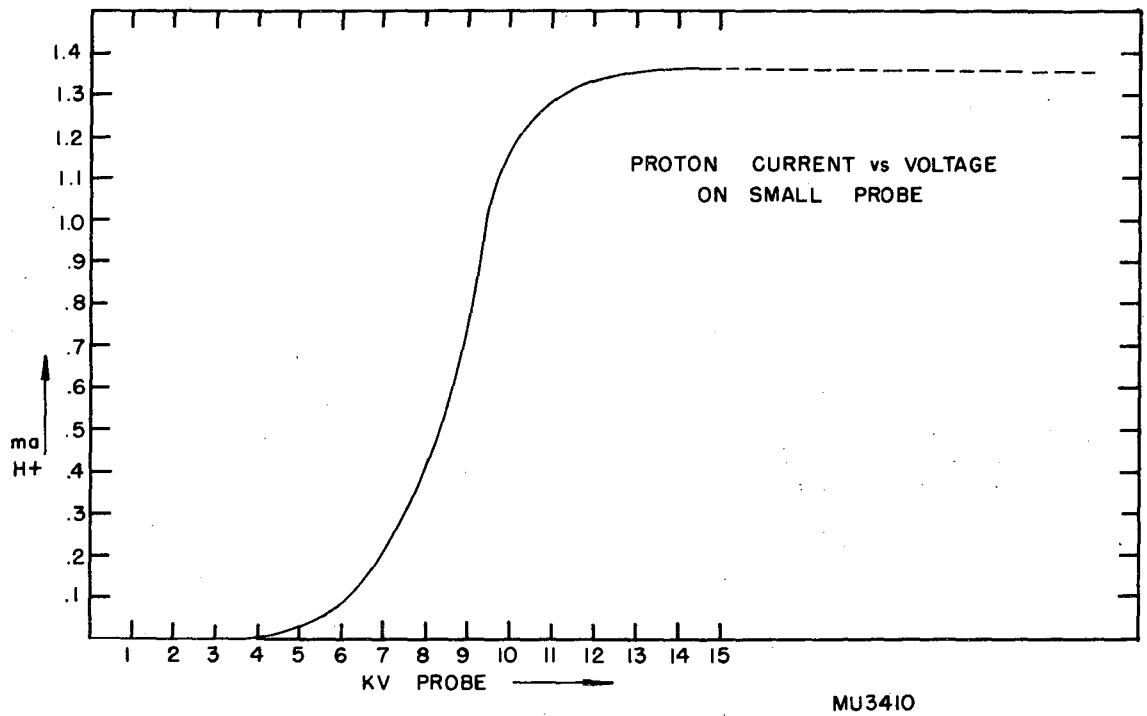
PROTON CURRENT vs VOLTAGE
ON SMALL PROBE
ma
H+
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
KV PROBE
MU3410

FIG. 2

192181

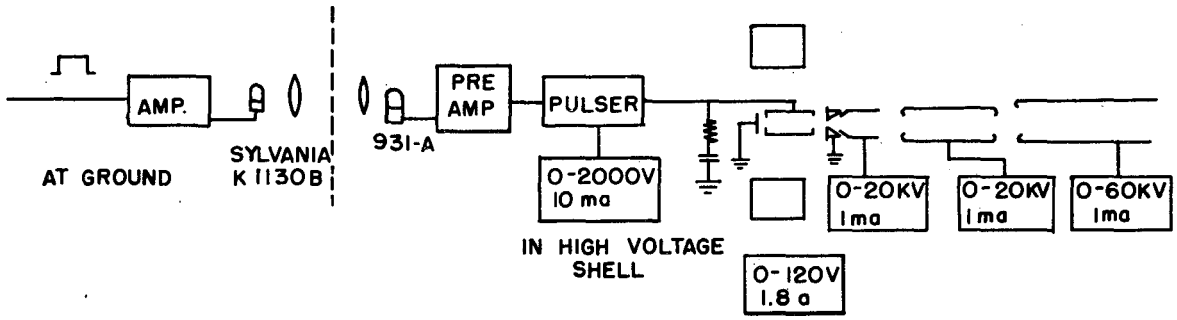

FIG. 3

BLOCK DIAGRAM OF

ASSOCIATED ELECTRONICS

MU3411