AURORA*, AN ELECTRON ACCELERATOR

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Electron Beam Specifications

Aurora was designed to produce a brief, intense radiation pulse, and the electrical specifications derive from the radiation output required. A "test volume" was defined that was roughly a meter cube. It was desired to irradiate this from one side to an average of 50,000 Roentgens throughout. In the laboratory, such yields can only be obtained as the bremsstrahlung from a high intensity electron beam stopped in a high density "converter". To maximize the efficiency of conversion of electron energy into photon energy, the highest possible kinetic energy was selected, consistent with the desire not to produce an excessive quantity of photo-neutrons. The kinetic energy chosen was 15 MeV. Calculations then showed that the dose in the test volume could be achieved with minimum electron energy if the radiation source were a uniformly energized surface about 1.5 m in diameter, placed near one face of the test volume (Figure 1). This source surface is the converter, which must be illuminated by a fairly uniform electron beam. The total charge of 15 MeV electrons needed per pulse was calculated to be about 0.2 Cb. An electron beam pulse duration of 120 ns was chosen to give the desired radiation pulse duration to allow for the finite rise and fall times of the beam pulse. Thus an electron beam specification of 1.6 MA at 15 MeV was arrived at, giving a peak power of 24 terawatts and a total beam energy of almost 3 MJ per pulse.

Design Approach

The only electron beam sources with performances comparable to that required for Aurora are those in which the full accelerating potential is applied to a "cold cathode", a room temperature conducting surface housed in a vacuum "accelerator tube". Electric fields can be created at the cathode sufficient to release electrons freely without the need to heat the cathode. Sufficient current flows from the cathode to the nearby anode that the space charge reduces the field at the cathode to a low value, producing a situation that is stable if the pulse length is shorter than the time of formation of a vacuum arc. By using pulsed potentials of several megavolts, currents of the order of 100 kA had been obtained at the time the Aurora design was addressed.

A number of different energy sources had been used by various workers to provide the high current, high voltage pulse for the cathode. The most successful of these, was the Marx charged coaxial oil-filled Blumlein developed by Martin and Bernstein. A schematic of this design is shown in Figure 2. The Marx generator is a voltage multiplying circuit that uses dc charged capacitors to store the necessary energy and then deliver it at the very high voltage required. The Blumlein is a coaxial capacitor, which, having been energized in a microsecond time scale by the Marx, delivers a submicrosecond pulse to the cathode. This system was selected as the basis of the Aurora pulse generator. The principles and details of each part of the system will be discussed further in describing the actual designs realized in Aurora.

The Aurora electron beam specifications represented more than an order of magnitude increase in energy and power over previous accelerators. This increase was achieved by a combination of scaling in size and multiplexing four parallel systems. A program was carried out to determine the scaling laws, and to find solutions to new problems posed by the use of parallel systems, including the need for synchronization and for co-location of the separate radiation sources. This program culminated in the construction of a representative "quarter system". When this had been successfully tested the full Aurora system was completely fabricated, tested and placed in operation.

In the following description of Aurora the Blumlein is addressed first. The Blumlein is central to the design because it provides the electrical pulse that drives the accelerator tube and also defines the requirements for the Marx generator.

Coaxial Oil Blumlein

The basic circuit was developed for radar applications by A. D. Blumlein. The configuration and principle of the coaxial Blumlein pulse generator, due to Martin and Bernstein, are illustrated in Figure 3. It consists of three coaxial conductors, the outer, intermediate and inner cylinders. To the load, which is connected between the inner and outer, the generator presents the electrical characteristic of a simple coaxial transmission line formed by the inner(radius r_1) and the outer (radius r_3) cylinders, and having an impedance $Z = 60\ \varepsilon^{1/2}\ \ln \frac{r_3}{r_1}$ (ohms) where ε is the dielectric constant of the oil with which the system is filled.

In operation, the intermediate cylinder is initially charged to a voltage V. The energy required for the output pulse is now stored electrostatically in the capacitance between the intermediate cylinder and the other two, which both are at ground. No voltage appears on the load. The switch S_1 then closes, shorting the inner and intermediate cylinder together at the end remote from the load. A voltage discharge pulse travels along between these two cylinders toward the load end. There the pulse encounters an open circuit, (supposing that the switch S_2 is open). The voltage transient, by inverting the initial voltage between the inner and intermediate cylinders, produces a voltage 2V between the inner and outer cylinder; this is the open circuit output voltage of the Blumlein.

Suppose now that the switch S_2 is immediately closed, connecting the load between the inner and outer cylinders of the Blumlein. If the load matches the characteristic impedance $60\ \varepsilon^{-1/2}\ \ln \frac{r_3}{r_1}$, the voltage will fall to one half of the previous value, i.e. to V, the matched output voltage. The pulses injected and reflected back down the Blumlein will reflect from the other end and return after a time $2L\ \varepsilon^{1/2}/C$ where L is length of the Blumlein and $C/\varepsilon^{1/2}$ is the velocity of light in the medium. This is the output pulse duration of the Blumlein. In particular, if $r_3/r_2 = r_2/r_1$ (i.e. if the inner and outer transmission lines are of equal impedance) the stored energy is totally discharged within the pulse duration, after which the voltage is everywhere zero.

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*The Aurora project was funded by the Defense Nuclear Agency. The machine was designed and constructed by Physics International Company and is in operation at Harry Diamond Laboratories, White Oak, Maryland.

The switch S_2 clarifies the above discussion but is not an essential feature, since the Blumlein operation which would be the same if it were always closed. Such a switch is not always present in coaxial oil Blumleins, though one is used in Aurora.

Aurora uses four Blumleins, each of 21 ohm impedance and charged to 12 MV. This impedance is in the range where the stored energy is a maximum for a Blumlein of a given size. The load current of 1.6 MA becomes 400 kA per Blumlein at 15 MV for a load impedance of 37.5 ohms. The mismatch between the Blumlein and the load gives the increase of voltage from the 12 MV matched value to the desired 15 MV.

The physical length of each Aurora Blumlein is about 40 feet, determined by the desired pulse duration and the dielectric constant of the oil (2.4). The overall diameter is determined by the distances required to withstand the 12 MV charge voltage reliably; the outer diameter is 23 feet and those of the intermediate and inner are 18' 6" and 13' 4" respectively. Breakdown between the high voltage cylinder and ground can occur by sparks which propagate through the intervening oil; these discharges always originate at metal surfaces. The maximum field experienced by the cylindrical surfaces is on the inner cylinder (190 kV/cm), and this is consequently made of smooth and polished stainless steel to minimize the chance of breakdown. The other two cylinders are plain steel. All three are coated with a plastic (polyurethane) which improves the breakdown strength by about 10%. A higher field (270 kV/cm) exists at the toroidal edge of the intermediate cylinder; this can be withstood partly because discharges require a higher field to initiate at a negative surface.

The outer cylinder of each Blumlein forms part of the structural shell of the accelerator, while the inner two are supported by handing in a carefully designed way on nylon straps. In the lower Blumleins, the inner cylinder is actually buoyant, and the nylon straps hold it down. The two inner cylinders of each Blumlein together weigh more than 30 tons.

The switch S_1, consists of a region in which sparks are deliberately triggered to close in the oil over a distance of about 24" between the flat ends of the inner and intermediate cylinders (Figure 4). A trigger electrode with a sharp edge is placed about 3" from the inner cylinder. When the voltage has risen to -12 MV on the intermediate cylinder a +4 MV trigger pulse is applied to this electrode. Very high fields are produced at the sharp edge, and initiate multiple discharges that bridge the entire switch gap in about 150 ns. A photograph of the completed spark channels is shown in Figure 5. The sparks dissipate considerable energy, producing a mechanical shock, and leaving bubbles and carbon from decomposed oil. These are removed by an oil jit prior to the next pulse.

The triggered oil switch, which carries almost 1 MV, was developed especially for Aurora; previous systems allowed a single spark to form of its own accord. Command triggering was necessary here to synchronize the four Blumleins and to provide multiple channels to reduce inductance and thus improve switch risetime.

The switch S_2 in Figure 3 is present because during the charging of the intermediate cylinder and the inner cylinder potential moves off ground by more than 500 kV. It is desired to isolate most of this voltage from the tube. In an ideal Blumlein, this voltage would be zero. However, no hard connection between the inner and outer is possible because this would in effect short out the output pulse. Instead, a 30 μH inductor is used to make this connection, and the currents that charge the Blumlein flow in this inductor and create the voltage described, which is termed the prepulse. S_2 is thus referred to as the "prepulse switch" and is simply formed by making a short space between the inner cylinder and the connection to the tube. The oil filling this space breaks down rapidly at twelve pre-determined sites when the Blumlein output pulse arrives.

Marx Generator

The primary energy storage element of Aurora is a Marx generator that is capable of storing 5 megajoules (Figure 6). The generator is similar in operation to the classical Marx circuit in that its energy storage capacitors are charged in parallel and then discharged in series through spark gap switches. However, there are some important features of the Aurora Marx generator that require elaboration.

First, unlike an ordinary Marx generator, the Aurora Marx can be successfully operated at charging voltages less than 50% of the mean self-fire voltage of one of its individual spark gaps. This is an important feature in that it greatly reduces the incidence of premature firings. The Aurora Marx owes its wide operating range to the fact that it utilizes triggered, instead of self-firing overvolted spark gaps, at locations in the circuit where the over-voltage transients are known to be weakened by stray-capacity shunting. The probability of a prefire occurring in the system before full charge is reached is less than one percent. The trigger signals for the spark gaps are derived from the previous firing of other stages of the generator and coupled by liquid resistors.

A second important aspect of the Aurora Marx generator is that it is divided into four Marx sub-assemblies that are operated in parallel. The use of parallel Marx generators reduces the overall internal inductance of the circuit as well as lessens the severity of the requirements placed on the spark gaps. Four spark gaps in effect share the electric current flow and charge transfer that would otherwise be required of just one. In addition, the use of sub-Marxes, and in particular the choice of four units, provides a certain amount of additional efficiency in the use of available space. It should be noted that the fact that the Aurora system has four Blumlein circuits and four Marx generator sub-assemblies is a coincidence. In fact, the four Blumleins are connected to common output terminals of the parallel connected Marxes.

Each of the four Marx sub-assemblies is an identical 95-stage generator. The sub-assemblies share a common dc-charging supply and a common triggering source. They are suspended within the simulator tank by a network of nylon straps that are attached to a special support system, which allows each assembly to be moved laterally with respect to the other by means of hydraulic actuators. This movable support system is used to provide access for maintenance operations.

Each stage of a Marx generator consists of four 1.85 μF, 60 kV energy storage capacitors mounted together as a unit and electrically connected to provide a capacity of 1.85 μF at a working voltage of 120 kV. The stages are connected in a circuit that combines features of two basic Marx generators; the capacity-coupled Marx and the resistively triggered Marx. For this reason it is called a hybrid Marx.

The basic schematic of a representative portion of a hybrid Marx is shown in Figure 7. The major stray capacities, which play an important role, are shown in phantom and the dc-charging circuits are omitted for clarity. In addition to providing a wide operating range, the hybrid circuit exhibits a low jitter in the time required for all of its spark gap switches to close. For the Aurora Marx this time, called erection time, is approximately 1 μsec and has an r.m.s. variation of only 10 nsec. The four Marxes are triggered by a pulse from a single 600 kV trigger Marx contained in the same tank.

The spark gap switches use pressurized SF_6 up to 30 psig, and brass electrodes with a 3/4 inch spacing. The trigger electrodes are field-enhanced brass discs at the midplane. This combination of materials was found to give a reproducible breakdown voltage under conditions of fairly high current and charge transfer. The peak current in the Aurora Marx is about 150 kA, and the total charge transfer during the oscillatory current flow during and after Blumlein charge is of the order of 1-1/2 coulombs.

The Marx charging resistors are of copper sulphate solution in flexible vinyl tubing. This design has good high voltage properties and can withstand large quantities of energy deposited during faults.

When all four Marx assemblies are operated in parallel, the combined output capacity of 7.8×10^{-8} F and the internal inductance is ~ 12 μH. When charged to 120 kV, the open circuit voltage is 11.4 MV.

During the time that the generator is being charged, there is a possibility that, some event such as the spurious operation of a trigger generator, might cause the generator to fire prematurely. To prevent damage to other simulator components when this happens, the output voltage of the Marx is clamped to a safe level by an output shunt resistor. A pneumatic actuator connects this resistor at the start of a charging cycle and then disconnects it just before normal firing.

Accelerator Tube

The four Aurora Blumleins are connected to four entirely separate accelerator tubes. Each tube has three principal regions (Figure 8). The first region is the tube insulator, a plastic structure separating the vacuum region from the oil that fills the Blumlein. The output pulse of the Blumlein passes through the insulator, then travels through the second region, a vacuum-filled coaxial transmission line. In the overall design, the four vacuum coaxes bring the output pulses from the axis of the Blumleins, which are at the corners of a square about 25 feet on a side, to the immediate vicinity of the comparatively small test volume. Each vacuum coax terminates, physically and electrically, in the third region, referred to as the diode. Here the electron beam is accelerated from the cathode and stopped in the high Z-anode.

The oil/vacuum boundary formed by the tube insulator has the shape of a fifteen foot long cylinder, ten feet in diameter, whose axis coincides with that of the Blumlein. The cylinder is formed (Figure 8) from forty identical Lucite rings, about ten feet in diameter and 4 in. thick. These are separaged by 1/2" thick aluminum rings.

Figure 8 illustrates the tube insulator cross section. The two adjacent aluminum rings serve to keep the electric field in the Lucite nearly axial on average. The field is thus inclined at about 45° to the actual plastic-vacuum interface, which is machined to form a smooth, conical bore. The field that the interface withstands is maximized by the choice of the 45° angle, which helps direct electrons emitted from the plastic or aluminum surface away from the Lucite and thus avoids electron multiplication. Still, a total length of 13' 4" of plastic is required to withstand the 15 MV, 125 ns pulse reliably.

The vacuum seals between the tube insulator rings are small diameter o-rings. A total of more than one mile of these are used in the four Aurora tubes. The stack of rings is subject to the external atmospheric pressure, a similar pressure from the head of oil and vertical bouyancy forces in excess of its weight. It is held in compression by external nylon rods. The high voltage end is closed with a metal dome that connects, via the prepulse switch, to the Blumlein output. To this dome is attached the negative high voltage electrode, which is cantilevered within the vacuum.

The negative high voltage conductor extends along the tube axis from the high voltage end and exits from the tube through a six foot diameter aperture at the ground end. At this point, it becomes the inner conductor of the vacuum coax (Figure 8). On leaving the tube, the vacuum coax bends through an angle of 45° with respect to the Blumlein axis, and is thus aimed towards the overall centerline of the four Blumlein array. The outer conductor of the vacuum coax is four feet in diameter over a fifteen foot long straight section leading to the diode region.

The high voltage inner conductor of the vacuum coax is 21" in diameter, and thus the coax has a 47 ohm characteristic impedance. At 15 MV, the field on the inner conductor surface is just over 700 kV/cm. This field is large enough to produce electron emission far in excess of the 400 kA design current. The fact that electron currents of this magnitude do not flow directly from the inner to the outer conductor, shunting the diode, is due to the azimuthal magnetic field produced by the current in the inner conductor. It can be shown that if this current exceeds

$\frac{V}{Z}\left(1 + \frac{2\, m_o c^2}{eV}\right)^{1/2}$, where V is the applied voltage and Z the characteristic coax impedance, an electron emitted from the inner conductor returns to the inner without reaching the outer. The factor $\left(1 + \frac{2\, m_o c^2}{eV}\right)^{1/2}$ is about 1.03 at V = 15 MV. It may therefore be postulated that if the diode impedance is a little less than that of the coax, then once the diode current has been established, radial current flow in the coax is prevented. This effect is termed "magnetic insulation".

It is possible to measure the current in the outer conductor at both ends of the coax and show that no more than 5 - 10% of the current can be flowing radially in between, i.e. that 90 - 95% of the current reaches the diode. It is not necessary that the inner conductor be polished or even smooth. Thus the vacuum coax functions as designed. The "single particle" view presented above may not be the current interpretation of the magnetic insulation process, however, as will be idscussed below.

At the output end of the vacuum coax is the diode region. This is created by ending the 21" diameter inner cylinder in an elliptical toroid of minor diameter 2", and closing the outer cylinder with a metal plate (Figure 9). The torus, like the inner conductor of the vacuum coax is of aluminum. The torus and the plate are not quite parallel. The region of the torus constitutes the cathode and emits electrons which are accelerated to the ground plate, the anode, about 18" distant. The high-Z converter consists of about 0.09" of tantalum mounted on the anode plate, which is fabricated from aluminum thick enough to stop electrons emerging through the tantalum and to withstand atmospheric pressure.

The simplicity of the configuration finally adopted for the diode disguises the fact that it was one of the most difficult parts of the machine to design. The prime concern arises because the bremsstrahlung created by 15 MeV electrons is forward directed with a half angle of about 10%. The electron trajectories at the anode must therefore be aimed towards the central region of the test volume, or much of the photon energy will not pass through the test volume. The electron trajectories are determined by the applied electric field geometry, by space charge electric fields and by the self magnetic field of the beam. In a case such as the present one, where the influence of the magnetic field is strong, there is a tendency for the beam to form an axial pinch, which results in a very large spread in electron incidence angles at the anode. Mutual crossover of trajectories makes it impossible to obtain satisfactory estimates of the electron flow using computer codes, while exact scaling from experiments with smaller beam currents and voltages is not possible. The final diode design was arrived at only after experimentation with a full Aurora "quarter system". Presious investigation had included experiments at up to 6 MV, approximate analysis and computer calculations of beam flow.

The diode impedance is stable to better than 10% throughout most of the pulse. It tends to be somewhat lower than the design value of 37-1/2 ohm, so that the maximum electron beam parameters are perhaps 14 MeV, 450 kA per diode rather than the nominal 15 MeV, 400 kA. The highest impedance obtainable proved to be about 35 ohm, and this fact lends support to the possibility that a portion of the electron flow reaching the anode originates far away in the vacuum coax region. On this view, the magnetic field in the coax does not return all emitted electrons to the inner conductor in the manner suggested by single particle theory, but guides them along equipotentials towards the diode. One such "parapotential flow" model predicts a maximum impedance as measured at the diode of 39 ohm; the single particle model suggests that impedances up to about 46 ohm should be possible.

Another important requirement of the diode is that the current density at the anode be low enough to avoid damage. Replacement of a damaged anode entails a 30 minute pump down time, and several hours more if exploded metal fragments have to be recovered from the tube insulator. The tendency of the beam to pinch in the anode cathode space due to its self magnetic field increases the current density at the anode. It was recognized that this effect, which is hard to predict quantitatively, might result in current and energy densities that high atomic number metals could not survive.

In practice, the electron beam is fairly broadly spread over the anode, with the maximum intensity regions consisting of an annulus whose diameter is approximately that of the torus and a central spot which is due to incipient pinching. The central region of peak intensity damages most high-Z converter materials tried, such as thick layers of tungsten alloys and tantalum. The damage mechanism is principally midplane spall, plus shattering in the case of the tungsten alloys. It was found that many 0.002" foils of tantalum survived the beam pulse where 0.015" sheets were destroyed. In the thin foils, accoustic waves relieve the pressure during the pulse duration. Only the foils nearest the cathode were still spalled or melted, probably by low energy, short range components of the beam. It was necessary to place a layer of steel on top of the 0.002" tantalum sheets in the central region of the anode, accepting the reduction of x-ray output produced by the lower-Z material. Steel survives because it receives a smaller pressure pulse and has a higher strength.

Overall System Design and Operation

The Aurora pulser system is housed in a single large tank that is approximately 135 feet long, 60 feet high, and 50 feet wide (Figure 10). The four Blumleins and accelerator tubes are arranged in a two-wide by two-high array. The tank requires 1.5 million gallons of insulating oil to fill it and weighs about 7500 tons when full. The oil is stored in external tanks, and can be transferred in about 1-1/2 hours. With the oil removed the entire system can be raised by hydraulic cylinders so that the weight is supported on wheels and then it can be rolled back 70 feet from its operating position for maintenance work.

During operation, the Marx generator is charged over a period of two minutes to a maximum of 120 kV. When full charge is attained, the Marx output shunt resistor is disengaged in preparation for firing. The Marx is on command, triggered, and when all its switches have closed, it begins to discharge into the Blumleins. It is necessary to charge the Blumleins toward a voltage of ~ 12-1/2 MV with the firing of the Blumleins occuring at 12 MV. The Marx has an open circuit gain of 95 which, at 120 kV charge, gives an output voltage of only 11.4 MV. The remaining voltage is gained by the 60 percent larger output capacity of the Marx over that of the Blumleins. A total voltage gain of 105 is realized. The use of resonance charging to supply additional voltage gain leads to a loss of energy transfer efficiency of only 7 percent which is readily acceptable in exchange for the simplification of a reduced number of series stages in the Marx generator.

Figure 11 is an oscilloscope recording of the resonance charging waveform. When the Blumleins have reached the desired charge level their switches are commanded to close. Once the Blumlein switches have closed, the Marx generator is essentially decoupled from the circuit. The output voltage of each Blumlein is monitored by means of a resistive voltage divider that is connected in parallel with the accelerator tube. An example of the voltage output wave is given in Figure 12.

The accelerator tube current is monitored by means of resistive shunts that are inserted in the outer conductor of the vacuum coax section. Figure 13 is an example of the output current waveform.

The combined radiation output of the four accelerator tubes, is illustrated by the detector waveform given in Figure 14.

Aurora was placed in routine operation at Harry Diamond Laboratories, White Oak, Maryland in May 1972.

References

1. B. H. Bernstein and D. F. Martin, U.S. Letters Patent No. 3505533, "Shielded High Voltage Pulse Generator".
2. W. T. Link, "Electron Beams from 10^{11} -10^{12} Watt Pulsed Accelerators," IEEE Transactions on Nuclear Science, No. NS-14, No. 3, 777, June 1967.

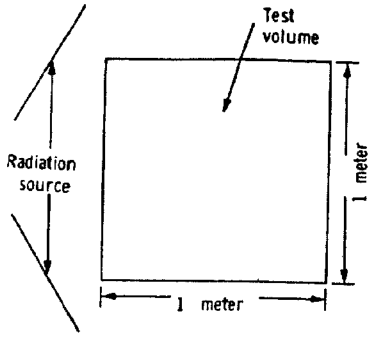

Fig. 1. RADIATION SOURCE AND
TEST VOLUME

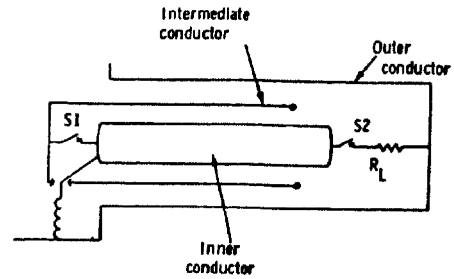

Fig. 3. BLUMLEIN CONFIGURATION

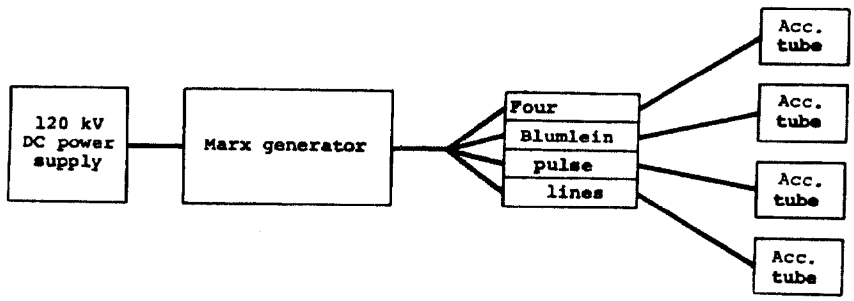

Fig. 2. SCHEMATIC OF AURORA PULSER

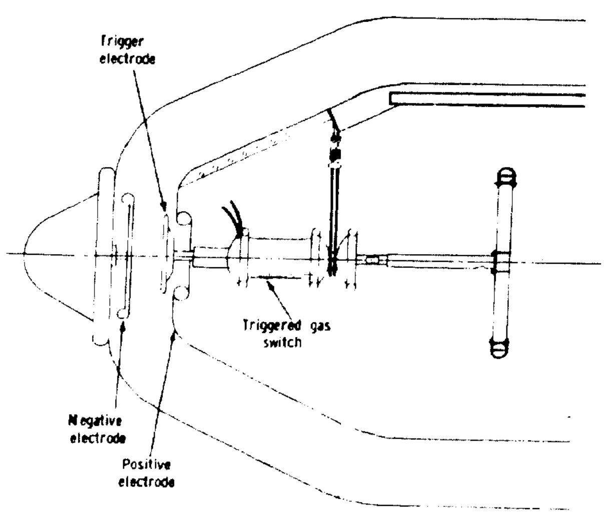

Fig. 4. AURORA OIL SWITCH

Fig. 5. SPARK CHANNELS IN
BLUMLEIN SWITCH

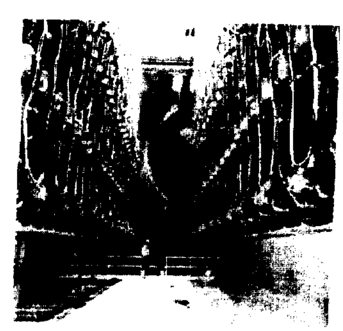

Fig. 6. INTERIOR VIEW OF
MARX GENERATOR

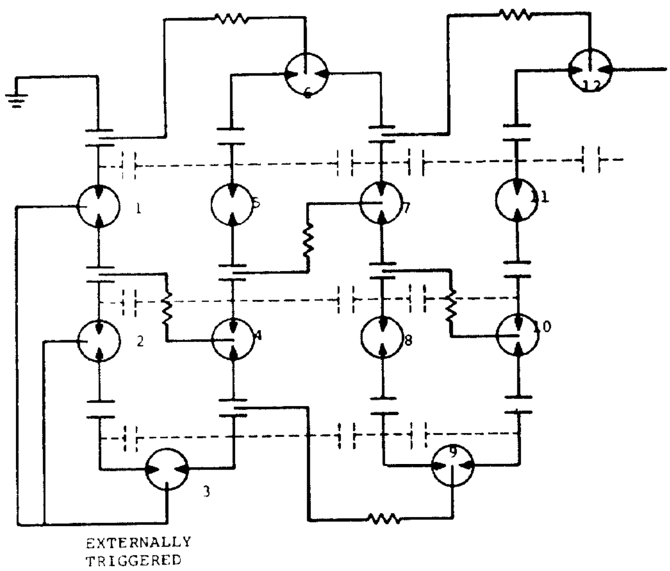

Fig. 7. HYBRID MARX GENERATOR CIRCUIT

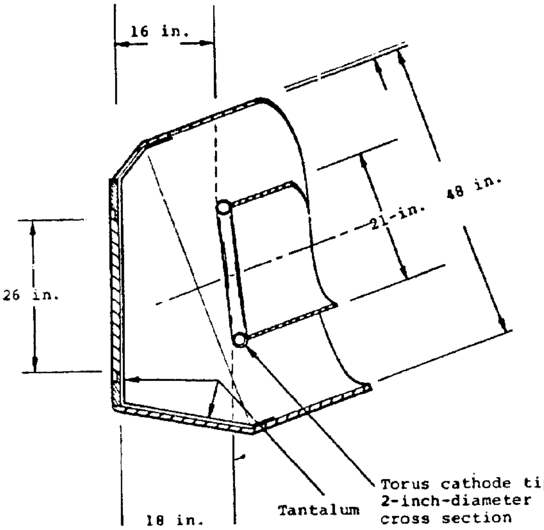

Fig. 9. ACCELERATOR TUBE CATHODE

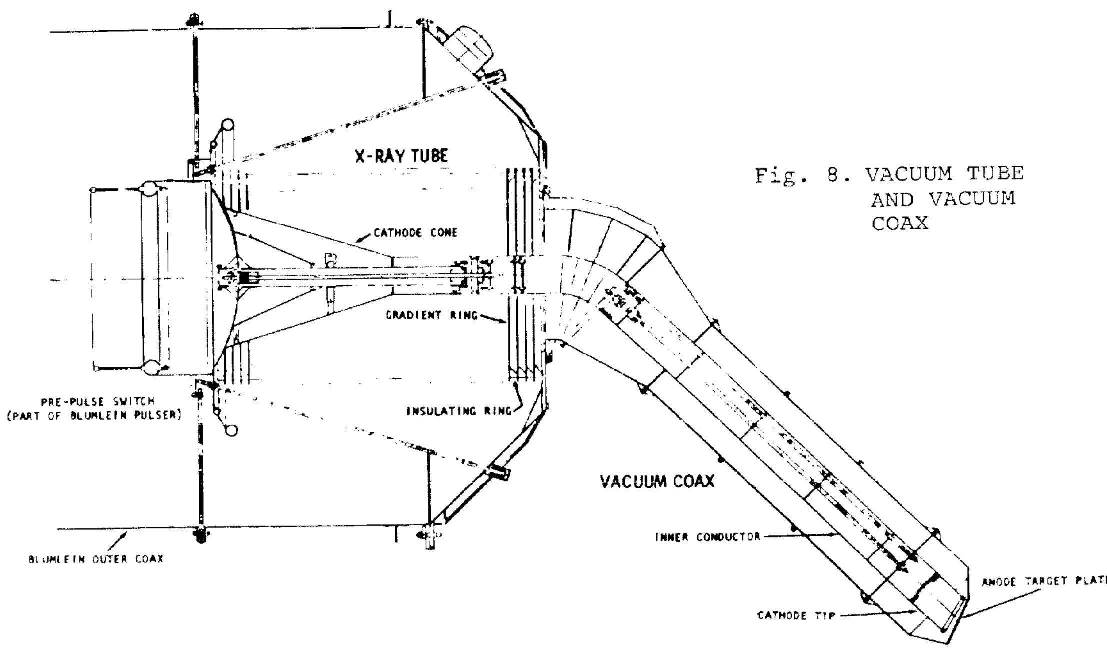

Fig. 8. VACUUM TUBE AND VACUUM COAX

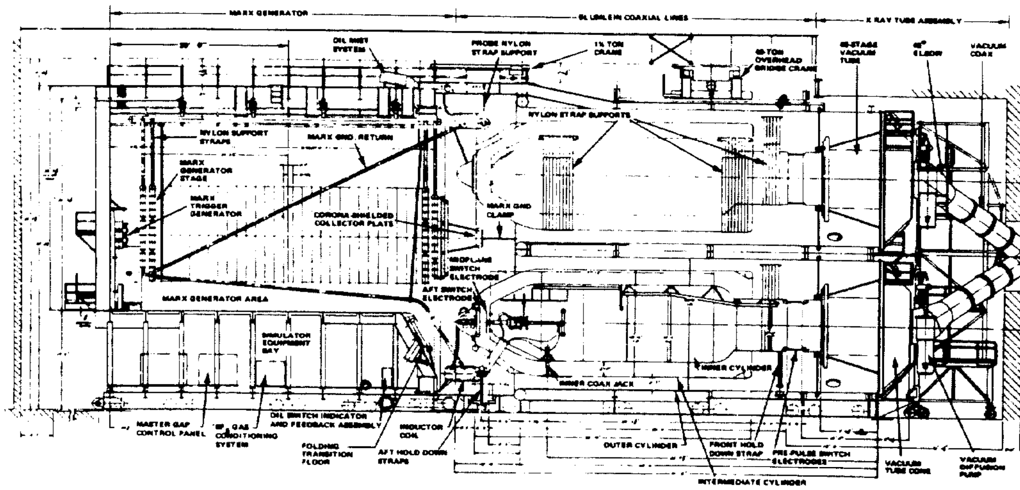

Fig. 10. AURORA PULSER SYSTEM- SIDE SECTION VIEW

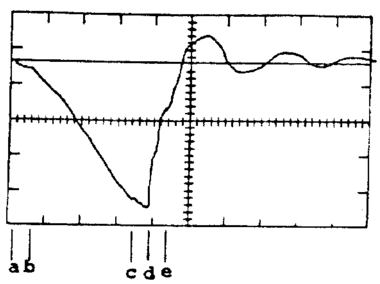

Fig. 11. PULSE-CHARGE MONITOR WAVEFORM
TIME: 500 nsec/div VERT: 2.7 MV/div

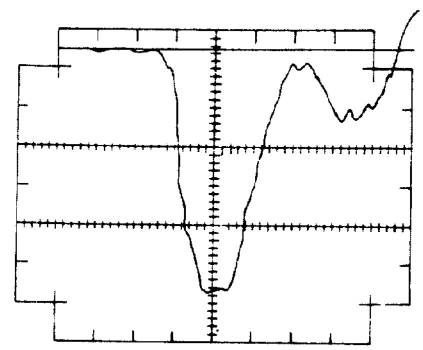

Fig. 12. TUBE ENVELOPE VOLTAGE
100 nsec/div

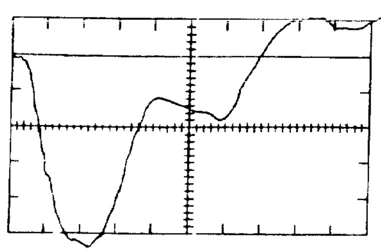

Fig. 13. TUBE CURRENT WAVEFORM
100 nsec/div

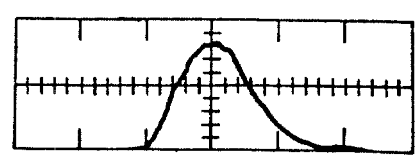

Fig. 14. RADIATION OUTPUT WAVEFORM