THE USE OF AN ELECTRON GUN IN THE VOLTAGE STABILIZER
OF THE RICE INSTITUTE HIGH VOLTAGE GENERATOR

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In the successful operation of a Van de Graaff machine, it is necessary that some provision be made to maintain the generator at a constant potential. Otherwise, fluctuations in the energy of the bombarding particles introduce difficulty in obtaining accurate experimental results. The energy of the beam striking the target can be selected by means of a magnetic or electrostatic analyser. It is necessary that the bombarding particles do not vary from the energy chosen by the magnetic or electric field strength and the placement of the slit system. Otherwise, fluctuations in beam energy will result in fluctuations of beam intensity at the target.

The Rice Institute Van de Graaff machine utilizes a magnetic analyser for selection of beam energies, as shown schematically in Figure 1. The accelerated particles enter the magnetic field which is obtained by use of a ring magnet, and are bent in circular paths. The radii of these paths are dependent upon the energies of the particles. The narrow slit at the lower end of the analyser further defines the energy of the particles which may pass through to the target. Some loss of resolution results from the finite dimensions of the slits, but intensity considerations dictate this condition.
Figure 1
It is necessary to maintain the potential of the generator at the proper value, so that the main part of the beam will pass through the defining slit. A number of factors are responsible for an energy spread of the beam coming from the accelerating tube. These include voltage fluctuations of the high potential electrode of the generator, the initial spread of velocities from the ion source, and the production of secondary ions by collisions of the primary ion beam with residual gas molecules in the accelerating tube. This energy spread can be roughly represented as shown:

![Energy Distribution Diagram](image)

The average energy maintained by the generator is represented by $E_0$. If the magnetic analyser is set to let through particles of energies $E_0 - \Delta E$ to $E_0 + \Delta E$, it can be expected that the target will receive the optimum beam intensity. If the generator potential should fluctuate while the analyser remains fixed the result will be a shift of the peak of the energy distribution, so that the maximum number of particles will not pass through the slit.
A system of voltage stabilization of the generator was devised by B. E. Watt. The defining slit jaws at the lower end of the magnetic analyser are insulated. The potential of the jaws due to the beam of charged particles incident upon them controls a circuit which in turn varies the intensity of a beam of electrons passing back up through the accelerating tube to the high voltage electrode. This beam of electrons has an equilibrium value when the generator is at a set potential. A change of potential results in a negative or positive change in the electron beam current, resulting in a correction of the charge on the high potential electrode.

A shift in the energy $E$ of the generator will result in a change of the radius of curvature of the path of a particle in the analyser for a given magnetic field $B$. Neglecting relativistic considerations, which is permissible at the energies of accelerated particles in the Rice high voltage machine, the change in radius is given by

$$\Delta R = (\text{constant}) \frac{\Delta E}{E^\frac{1}{2}}$$

for a change in energy $\Delta E$. This change in radius results in the maximum beam intensity falling to one side of the slit opening, thus increasing the current to one of the insulated slit jaws, and correspondingly decreasing the current to the other jaw.
The circuit as shown in Figure 2 controls an electronic tube which sends current back up the accelerating tube to the high potential electrode. In equilibrium, when the potentials on the grids of the 6SJ7's are equal, the circuit sends an equilibrium value of current up the tube. This return current must be balanced by the amount of current sprayed on the belt of the machine, so that the difference value keeps the high potential electrode at the desired potential. If the energy of the beam deviates, resulting in a change of potential on the two grids of the 6SJ7's, both tubes operate to either increase or decrease the current sent back up the tube, thus correcting the potential of the machine until the equilibrium value of the system is again reached.

An example of the order of magnitude of the correction required may be given by considering the high potential electrode of the generator and the ground as forming a condenser of capacity \( C = \frac{Q}{V} \). Considering low frequency changes of potential, a value of the charge \( \Delta Q \) needed to correct a potential change of \( \Delta V \) may be obtained from \( \Delta Q = C \Delta V \). The electron tube sending current back up the accelerating tube operates at an equilibrium current \( I \) when the heavy particle beam is centered on the slit jaws. When a change
\( \Delta V \) of the generator potential occurs, the electron tube must produce a change of electron current \( \Delta I \) which goes up the tube, so that the charge on the high potential electrode may be increased or decreased such that \( \Delta V \) goes to zero.

\[
\Delta I = \frac{\Delta Q}{\Delta t} = C \frac{\Delta V}{\Delta t}
\]

In this expression \( \Delta t \) represents the time interval required for the return electron current to bring the generator back to the correct potential. This time may be arbitrarily set within the limits imposed by the characteristics of the control circuit.

The unregulated voltage fluctuations in the Rice Institute generator have been determined to be of the order of \( \Delta V = 5000 \) volts, and the capacity of the machine to be \( C = 5 \times 10^{-11} \) farad. If an arbitrary \( \Delta t = 10^{-2} \) second is chosen, the current change \( \Delta I \) can be calculated to be 25 micromperes. However, this calculation gives only the order of magnitude of the current needed, since the stabilizer continuously corrects error voltages, preventing voltage changes as high as 5000 volts from occurring. Thus, in operation, small current changes may be expected.
The 01-A used in the circuit shown in Figure 2 is a triode with a directly heated filament. The plate has a V-shaped series of small holes drilled in line with the filament so that a fraction of the plate current passes through the openings and continues up the tube to the insulated electrode of the generator. This arrangement is unsatisfactory due to the random emission of electrons into the tube. Due to electron multiplication on the electrodes of the accelerating tube and variations in emission along the length of the filament, the operation of the stabilizer is very erratic. The fraction of the plate current which passes through the series of holes is of a much lower order than the current which reaches the high potential electrode, so that electron multiplication must occur. The difficulty is the unstable character of the multiplication.

To rectify this situation it was decided to replace the 01-A with an electron gun of simple design which would send a well defined beam of electrons back up the center of the accelerating tube, thus avoiding the electron multiplication effects due to the random orientation of electrons given by the 01-A.

Several restrictions were placed upon the design features of the gun which increased the difficulties connected
with producing a successful gun. Most electron guns which produce high beam currents of the order of 15-30 microamperes utilize the simplifying features of indirectly heated oxide coated cathodes. This gun operates in a vacuum of the order of $10^{-5}$ mm of Hg, so that an oxide coated cathode cannot be successfully used since poisoning effects are appreciable to pressures as low as $10^{-6}$ to $10^{-7}$ mm of Hg. Thus, it is necessary to use a directly heated cathode which is accompanied by a number of troublesome features which will be discussed below.

Another restriction placed upon the gun is simplicity. It must be simple to operate and provision must be made for ease in the replacement of the filament with an approximate duplication of the characteristics of the gun. It was also decided to make the gun of such geometry that it could fit into the accelerating tube through the 1½ inch hole provided for the Ol-A, since drilling a larger hole could easily open leaks in the system.

The gun, shown in Figure 3, is of a simple single anode structure with a control grid and a magnetically clad focusing coil. All major elements of the gun except the filament leads are made of magnetic material in order to provide magnetic shielding for the filament and the electrostatic field between the grid and the
Figure 3

ELECTRON GUN

SCALE
2 INCHES = 1 INCH

KOVAR SEALS

BASE PLATE

ANGODE
MAGNETIC COVERING
MIKROY INSULATION
ELECTRON GUN
FILAMENT
FILAMENT COVER
FILAMENT LEADS
GRID
GAP
COIL WINDING
MAGNETIC COVERING
anode. This is necessary in order to secure stable characteristics of the gun.

The most serious problems encountered with this type of gun are concerned with the electron source for the gun. Since it is necessary for the cathode to be directly heated, it is best to use tungsten wire. This wire is very rugged and more trouble free than any of the other directly heated types of emitters. The use of a filament of this type introduces a number of other problems.

Heating of the elements of the gun is a serious source of trouble. All parts of the gun must be so constructed as to withstand temperatures on the order of several hundred degrees centigrade. For instance, the Kovar seals of the gun will become coated with zinc after heating the filament of the gun for a short period of time if brass is used in the gun. This zinc comes from the surface of brass elements of the gun due to the rather high vapor pressure of zinc at intermediate temperatures. Thus brass must be avoided as a constructional material.

Tungsten filaments have a tendency to deform upon heating unless great care is exercised in mounting them in such a way as to avoid subjecting them to stresses. Helical coils are very subject to deformation, resulting at times in shorting the filament to the grid and always
making extremely difficult the duplication of gun characteristics upon replacement of the filament. This difficulty may be overcome by using a straight filament wire, attached to the ends of the filament leads.

The use of a tungsten filament introduces the problems of emission from the filament and its evaporation. The emission density is given by Dushman's relation.

\[ I = AT^2 e^{-\frac{bo}{T}} \]

\( I \) = current density in amperes per square centimeter

\( A \) = a constant for the material used

\( T \) = cathode surface temperature in degrees Kelvin

\( bo \) = temperature equivalent of the materials work function

= 11,600 Vw

\( Vw \) = work function of the emitter in volts

From this relation it is seen that the maximum permissible current density from the emitting surface is determined by the maximum surface temperature at which the emitter can be operated commensurate with a reasonable lifetime of the filament. The lifetime in this case
depends not only upon the evaporation of the metal, but also upon the sputtering of the metal due to positive ion bombardment which is appreciable up to \(10^{-6}\) to \(10^{-7}\) mm. of Hg.

Another serious problem due to the use of a directly heated cathode is a suitable source of power for heating the filament. Alternating current cannot be used because of the introduction of an A.C. voltage between the cathode and grid, which produces an alternating variation in the beam current. This is undesirable because it would introduce a ripple in the high potential of the Van de Graaff machine. Because of this, a selenium rectifier bridge was used, as shown in Figure 7. The ripple in beam current using this power source is reduced by a factor of around twenty. Batteries are not used as a power source, since a heating current of 4 to 8 amperes is required.

The irregular surface of the filament poses a problem in the focusing and prevention of fringing of the beam, due to the non-constant orientation of the electrons passing through the grid and plate apertures to the focusing field. This problem is best met by continuing the axis of the coil for a distance sufficient to block out the non-focused electrons.

Ease in mounting new filaments and reproducing the characteristics of the gun are the considerations which
prompted the construction of the grid, anode, and coil as a unit. The entire unit can be removed in order to replace an old filament with precision. Thus the difficulties in connection with correctly positioning grid, plate, and focusing coil have been obviated once the gun has been assembled. The problem of the grid to filament spacing has been dealt with by using heavy, stationary filament leads, and always attaching filaments of the same geometry in a standard manner. This particular point is of great importance, since a small deviation in filament to grid spacing can result in a large change in tube characteristics.

The gun is magnetically focused by a coil covered with monel metal. Since the covering of the coil has low reluctance, the current necessary to produce focusing is reduced. The fringing about the gap of non-magnetic material produces a small, localized focusing field of the proper shape for good focusing. The focusing characteristics of the gun are shown in Figure 4.

The testing of the gun has been carried out on an apparatus simulating the lower end of the accelerating tube of the high voltage generator. The characteristics are shown in Figures 4, 5 and 6. The ratio of beam current to plate current shown in Figure 6 was found to be too great. Since it is desirable to have total plate currents
FOCUSING CHARACTERISTICS
OF THE ELECTRON GUN

Figure 4
Figure 5

Beam current as a function of grid voltage.
FRACTION OF TOTAL PLATE CURRENT IN THE BEAM

\[ R = \frac{\text{BEAM CURRENT}}{\text{PLATE CURRENT}} \]

Figure 6
of the order of 0-1 milliamperes in the circuit designed by B. E. Watt, this ratio would result in electron beam currents of the order of 0-500 microamperes. Beam currents greater than 30 microamperes are desirable, since the spray-on cannot supply enough current to overcome electron currents greater than this. It is also necessary to consider the production of X-rays by the electrons striking the high potential electrode. This effect must be kept as low as possible by keeping the electron current low. In order to reduce the ratio to a suitable value, a circular plug containing an aperture was placed in the end of the focusing coil. This plug reduced the ratio of beam current to total plate current to an average $R$ of 0.05. An added advantage due to this change is better definition of the beam.

The gun itself has the characteristics of a simple triode with an amplification factor of about 25 without the aperture for reducing the ratio of beam current to total plate current.

A circuit, shown in Figure 7, similar to that due to B. E. Watt was used with suitable modifications made in order to use a higher voltage gun. By using a zinc sulfide screen to observe the focus of the gun, it was found that better focusing occurred at higher plate voltages of the gun, so that a value of 800 volts was decided upon as a
compromise between less sharp focusing and the disadvantages contingent upon the use of higher voltages.

The modified circuit of Figure 7 makes use of a separate grid bias for the gun. The various resistances were made variable in order to give flexibility in the adjustment of the circuit. It was found that the values given by Watt were satisfactory with this gun.

In operation upon the Rice Institute Van de Graaff generator, the gun produced a high degree of stabilization. Without regulation, the intensity of the heavy particle beam at the target varies from zero to some maximum value. With the stabilizer in operation, the intensity never falls off to zero, as long as the heavy particle beam does not cut off. The intensity does vary as much as 20 to 30% at energies of around 740 kev, but at higher energies of the order of 1.2 Mev the beam intensity to target is maintained constant to within 5 - 10%.

The stabilization is a function of the return electron current. At 740 kev regulation was obtained with electron beam currents of 5 to 20 microamperes. The regulation was satisfactory with a return current of 5 microamperes, but was somewhat steadier at 20.

A count of the X-rays in the operations room of the high voltage lab showed that the X-ray intensity increased
by a factor of approximately 1.5 to 1.9 when electron beams of 20-25 microamperes of current were sent up the tube to the high potential electrode. This is not an excessive increase in the count.

At higher potentials of the generator, the regulator was found to be in need of a minor adjustment in order to simplify the operation. When a spark occurs in the generator, the high potential electrode is discharged, thus the beam of ions is no longer accelerated down the tube. However, the electron gun continues to send an equilibrium current of excessive value down the tube, so that the spray-on cannot build the potential back up. This situation can be rectified by turning off the gun and allowing the generator to rebuild its charge. In practice however, this would be a tedious procedure, so that it was decided to use a relay to put a large negative bias on the grid of the gun for a short period of time, in order to allow the generator to build up potential. The relay is operated by excessive currents in the cathode circuit of the gun. An added advantage with this scheme is that the relay will operate intermittently until the generator is back at the correct potential. At this potential the stabilizer will again regulate, preventing the generator from building a higher charge and again sparking.
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REFERENCES


3 - Zworykin, et. al., Electron Optics and the Electron Microscope