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The Magnetron

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INTRODUCTION

IN PRESENTING to you this youngest member of the electron tube family, I am both aided and embarrassed by its family history. I am aided by the fact that you are already acquainted with electrons, so that I need waste no time in explanation or argument regarding their existence. You believe in these little cannon balls which jump out of the hot filament, fly across the vacuum, and plunge into the anode. You have seen them heat the tungsten anode of an X-ray tube to its melting-point in a fraction of a second. Most of you believe that when a current flows through a wire it is these same little electrons, and nothing else, that stream through the wire, like water flowing through a pipe.

But while electrons are among your engineering acquaintances, they are not accepted, so to speak. They are associated with wireless magic and microamperes, read through a telescope. And so, as engineers, you view them with aloofness, as interesting playthings, not engineering tools.

It is quite reasonable that you should view them so, but you are wrong. Electron devices are not small, they are only young. They are growing up. You have heard of their slow development from microamperes to milliamperes. Since you last heard from them they have grown from milliamperes to amperes; and before you know it, before you know *them,* if you don't watch out, they will have grown to kiloamperes.

I therefore present to you, tonight, the magnetron as an engineering device. I shall suggest some applications. You, with your greater experience, can, I hope, think of many more.

I shall first state briefly what the magnetron is; then why it is, that is, the theory of its operation and how it is related to the other "trons"; then what it will do; and, finally, what I hope it will do.

DEFINITION

"Magnetron" is a Greeko-Schenectady name, as Mr. Lee DeForest calls it, for a vacuum electric device which is controlled by magnetic field. It belongs to the kenotron family. Kenotron, which means, as those of you who are Greek scholars will readily recognize, a "thing with nothing in it," is a general term which we apply to all our vacuum thermionic devices. Examples of simple kenotrons are the X-ray tube and kenotron rectifier. The name pliotron is intended to mean a thing that amplifies; the dynatron, a thing that generates power; and the magnetron, a thing operated by magnetic field.

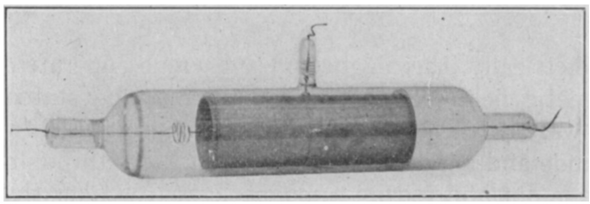

FIG. 1

Structurally, the magnetron is a simple kenotron whose elements are symmetrical about an axis. It may consist of a straight filament surrounded by a cylindrical anode, as in Fig. 1; or a straight rod-shaped anode, surrounded by a helical filament, as in Fig. 2; or it may consist of three elements, a filament, grid, and anode, all symmetrical with respect to a common axis, as in Fig. 3. Symmetry, circular symmetry with respect to an axis, is essential. The reason for this will appear later. The fundamental distinguishing structural feature of the magnetron is its symmetry.

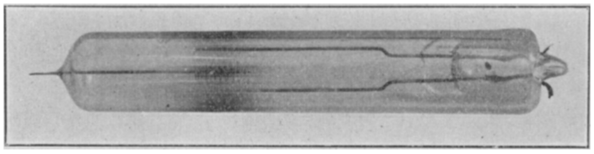

FIG. 2

A second structural characteristic, in addition to symmetry, is essential for a practical magnetron; namely, that it should be of such form that a magnetic field parallel to the axis can be conveniently and economically applied. This is accomplished in the tube shown in Fig. 1 by making the glass envelope a tight

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fitting cylinder, concentric with the electrodes, so that a solenoidal coil may be wound directly on the glass; and by slotting the anode longitudinally, so that the magnetic flux produced by the solenoid will not be neutralized by eddy currents. The slotting of the anode is especially important when high-frequency alternating magnetic fields are to be applied.

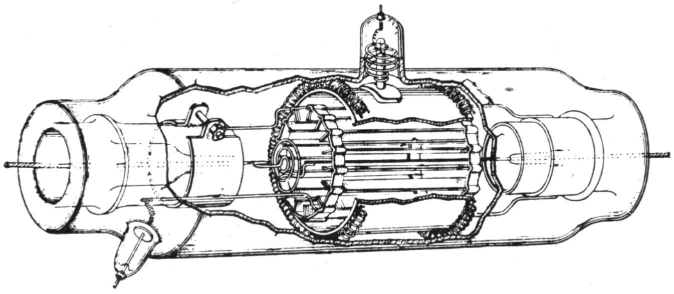

Fig. 3

Electrically, the magnetron is a valve, operated by magnetic field. Its characteristic may be stated as follows: If a constant voltage is impressed between cathode and anode, the current that flows through the tube is not affected by a magnetic field weaker than a certain critical value, but falls to zero if the field is increased beyond this value. The magnetic field must have its lines parallel to the axis of the tube.

This characteristic may be made clear by some examples.

Fig. 4 shows the tube and circuit. The cathode is a straight tungsten filament, the anode a circular cylinder. A battery, B_1, heats the filament to incandescence, and another battery, B_2, impresses a constant voltage between cathode and anode, the anode being positive. This is a plain kenotron arrangement, and if the temperature of the filament is high enough, a current will flow across the vacuum, as you know. The magnitude of the current will be limited either by the temperature of the filament or the voltage of the anode, whichever gives the *smaller* value of current.

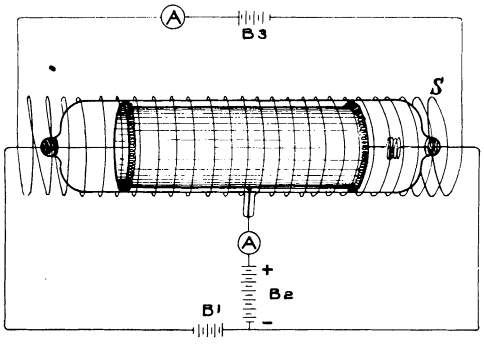

Fig. 4

The addition of a magnetic field, produced by the solenoid S, imposes a third type of limitation upon the current flow. If the field is weaker than a certain critical value, the full current will flow, limited only by filament temperature or voltage; if the field is stronger than this critical value, no current will flow. The action of the magnetic field is thus similar to that of a valve in hydrodynamics, or a contact relay in electrical circuits. In fact, the same characteristics would be obtained if the tube in Fig. 4 were replaced by a resistance, and the solenoid S, instead of being around the tube, were used to energize a relay that opened and closed the circuit of the battery B_2. As long as the magnetic field is weaker than a certain critical value, the relay remains closed, and full current flows; when the field becomes stronger than this critical value, it opens the relay, and no current flows. The magnetron relay has the advantage of no moving parts and no inertia—its speed is limited only by the time necessary to build up the magnetic field, which may easily be made less than one millionth of a second. It has the disadvantage that it is a high-resistance relay, since it requires a vacuum tube in the circuit.

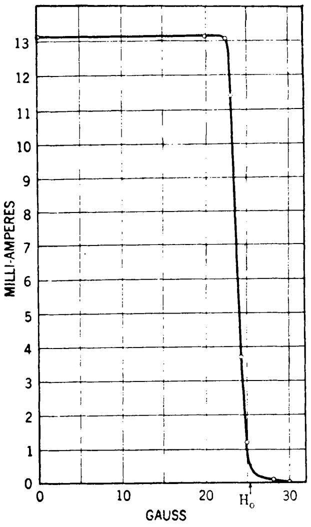

Fig. 5

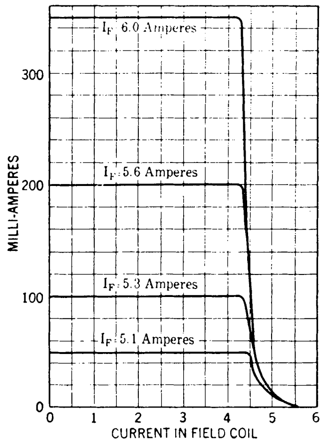

Fig. 6

A typical gauss-ampere characteristic is shown in Fig. 5. The abscissas are gausses, or lines per square centimeter, the ordinates current through the tube. The anode was a cylinder $1\frac{1}{2}$ in. in diameter and $4\frac{1}{2}$ in. long, the cathode a 4-mil straight filament. It is seen that for all values of the magnetic field less than 23 lines per square centimeter, the valve is wide open, and the same current flows through the tube as when the magnetic field is zero. For fields larger than 25 lines per sq. cm. the valve is closed, and no current flows. It will be noted that the transition from "open" to "closed" condition is not quite abrupt. This is due mainly to lack of symmetry. In a well evacuated perfectly symmetrical tube, the transition should be very nearly abrupt.

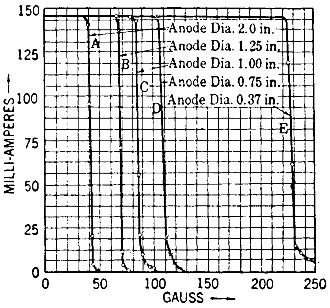

Fig. 7

In Fig. 5 the maximum current is limited by the voltage between cathode and anode. The effect of the magnetic field is the same, however, whether the maximum current is limited by voltage or temperature. This is shown in Fig. 6, which gives the characteristics of the same tube at four different filament temperatures. In the upper curve the temperature is high enough so that the current is limited only by the voltage. In the other three, the current is limited by the filament temperature.

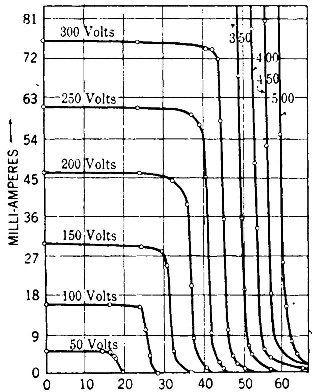

Fig. 8

The critical value of magnetic field that is just sufficient to close the valve depends only upon the diameter of the anode and the voltage across the tube. It is inversely proportional to anode diameter, and directly proportional to the square root of the voltage between cathode and anode. Its dependence on anode diameter is illustrated by Fig. 7, which shows the characteristics of four different tubes, with diameters from $\frac{3}{8}$-in. to 2 in., at the same voltage. The maximum currents are limited by filament temperature to the same value. It is seen that the 1-inch diameter anode requires twice as much field as the 2-inch one, and the $\frac{3}{8}$-in. one twice as much as the $\frac{3}{4}$-in. one; that is, the critical field is inversely proportional to the diameter.

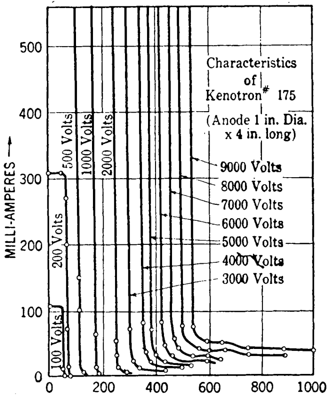

Fig. 9

The effect of varying the voltage is shown in Figs. 8 and 9, which give the characteristics of the same tube at different voltages. The anode in Fig. 8 was a cylinder 2 in. in diameter and 2 in. long; in Fig. 9 a cylinder 1 in. in diameter by 4 in. long. It will be noted that the field required to close the valve at 500 volts is only half as great as at 2000 volts, and one-quarter as great as at 8000 volts; that is the critical field is proportional to the square root of the voltage. Only the lower portions of the curves in Fig. 9 could be taken because of the excessive heating of the anode. The full current at 9000 volts is 100 amperes. This was reduced to a few milliamperes by the magnetic field alone.

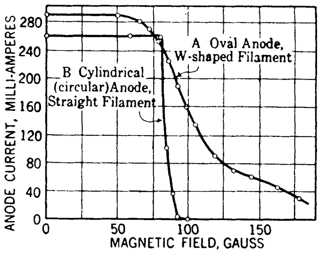

Fig. 10

The necessity for symmetry of construction is shown in Fig. 10. Curve *A* shows the characteristics of a magnetron, with straight filament and cylindrical anode 1 in. in diameter by 4 in. long, at 250 volts; curve *B*, that of a kenotron with *W* shaped filament and oval anode, $\frac{3}{4}$ in. thick by $1\frac{1}{2}$ in. wide by 2 in. long.

The necessity for making the lines of the field parallel to the axis of the tube is shown by Fig. 11. Curve *A* shows the characteristic of a 1-in. by 4-in. tube with field parallel to its axis; curve *B* the characteristic of the same tube at the same voltage with the lines of the field at an angle of 20 deg. to the axis of the tube.

A more sensitive form of magnetron may be made by putting the anode inside the cathode instead of outside, as in Fig. 2. The tube and circuit are shown in Fig. 12. The cathode is a helical tungsten filament, ¼ in. in diameter, the anode a straight tungsten wire $^1/_{100}$ in. in diameter. The magnetic field required to operate a magnetron with internal anode is smaller than for an external anode of the same dimensions by a factor equal to the ratio of the diameters of the cathode and anode. In the tube shown in Fig. 12 this ratio is 25, so that the field required to close the valve is only $^1/_{25}$ as great as for a tube of similar dimensions with external anode; *i. e.*, a tube with 10-mil straight filament surrounded by a ¼-in. diameter anode. The cutoff is less abrupt, however, in the internal anode tube.

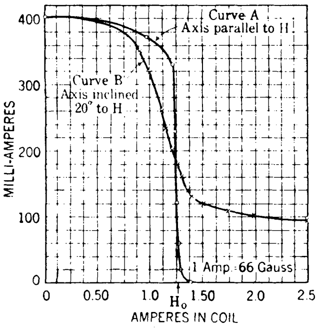

Fig. 11

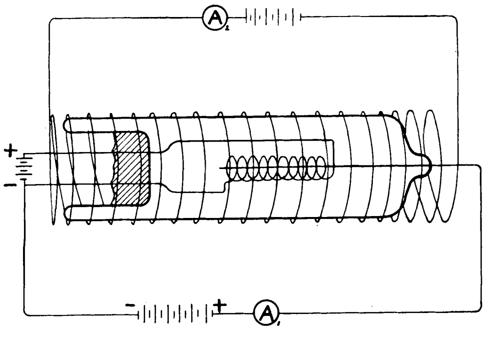

Fig. 12

Fig. 13 shows the characteristic of this tube at 110 volts. A rotating commutator interrupted the heating current during the brief intervals while the measurements were being made. At first glance one would say that this characteristic is not steep enough to be of any interest, like that of the unsymmetrical tubes shown in Figs. 10 and 11. It will be noted, however, that the fields required are manifold smaller than in Figs. 10 and 11, so that a field only ten times that of the earth is sufficient to reduce the current to half value, and the effect of the earth's magnetic field is clearly seen, shifting the whole curve to the right by $^6/_{10}$ of a gauss.

The slope of the curve is due to the initial velocities with which the electrons are emitted from the filament. These initial velocities are known, and it is possible to calculate their effect. The crosses in Fig. 13 show the calculated results, the experimental values being represented by the circles. If the initial velocities were very small, the characteristic would be represented by the vertical line H_o. This condition can be approximated by using a very low temperature filament.

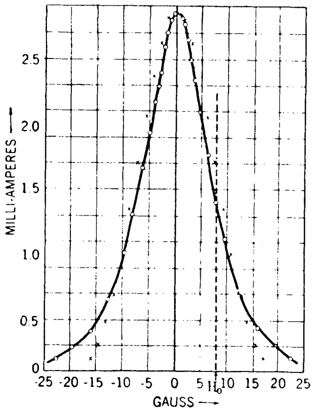

Fig. 13

Theory of Magnetron

The foregoing discussion has aimed to define what the magnetron is—an inertialess, high-resistance valve, operated by magnetic field. I shall now attempt to explain why it is—the theory of its operation.

The mathematical theory of the magnetron will be found in the Aug., 1921 number of the *Physical Review*. It need be referred to here only to point out that the solutions are simple and apparently rigorous and agree with the experimental facts outlined above.

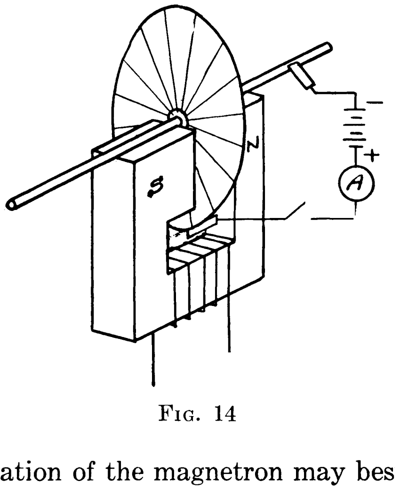

Fig. 14

The operation of the magnetron may best be understood from an analogy.

The magnetron is closely analogous to a direct-current motor running without load. In order to avoid commutators, I shall take the case of a unipolar motor (Fig. 14), composed of a slotted disk capable of rotating between the poles of an electromagnet. Current is led into and out of the disk by brushes on the axis and periphery respectively. When the switch is closed a large current flows, as indicated by an ammeter A, and the flow of current across the lines of the magnetic field develops a torque which starts the disk in rotation. The rotation develops a back e. m. f., which, if there is no resistance to rotation, will increase until it exactly equals the e. m. f. of the battery, and the current through the ammeter A will fall to zero. In practise the current does not fall quite to zero, because of the friction.

I have described the operation of the motor in ordinary engineering language. I will now describe it again in greater detail, using the language of electrons, but introducing no new ideas. Instead of the simple statement that current flows when the switch is closed, I will be more specific, and say that electrons flow; for it is electrons, and nothing else, that carry electricity through wires, and they flow from negative to positive, in this case from the axis toward the periphery. The disk begins to rotate because a conductor carrying current in a magnetic field is acted on by a mechanical force. Does the force act on the conductor or the current that is flowing in it? This question may be answered definitely. The force acts on the electrons, tending to make them move in spiral paths instead of radially. Since the electrons cannot move tangentially without taking the disk with them, on account of the slots, the disk begins to rotate. The electrons would drag the disk with them even in the absence of slots because of electric resistance.

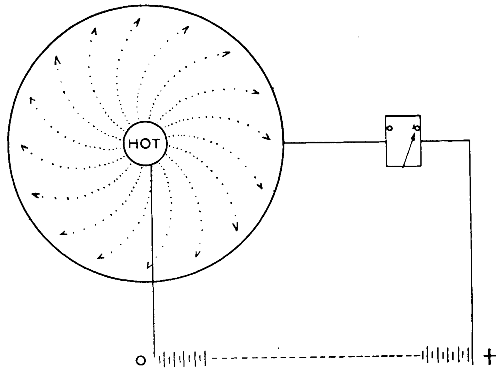

Fig. 15

The rotating disk carries the electrons with it, giving them a tangential velocity. The electrons will therefore be acted upon by an additional component of force, at right angles to this tangential component of velocity, that is, radially inward, in opposition to the impressed e. m. f. When maximum speed is attained, if there is no friction, the radial flow of the electrons is completely stopped by the back e. m. f. Their motion becomes entirely tangential, and the force acting on them entirely inward, in opposition to the e. m. f. of the battery. We thus have a simple case of a conductor at whose terminals an e. m. f. is impressed by a battery, but no current flows. The explanation of the lack of current is a back e. m. f., produced by the motion of the electrons in the conductor across the lines of magnetic force.

Turning now to the magnetron, which is shown in cross-section in Fig. 15, it is obvious that the electrons that start to move radially outward, under the influence of the impressed e. m. f., will be acted on by a tangential force tending to curve their paths into spirals, and that the tangential component of velocity thus imparted will react with the magnetic field (which is normal to the plane of the figure) to produce a radial component of force on the electrons, inward toward the filament, in opposition to the e. m. f. of the battery. If the magnetic field is sufficiently strong as shown in Fig. 16, this inward force, *due to the circular motion* of the electrons, will just balance the e. m. f. impressed by the battery. Hence the electrons, though perfectly free to move about in the vacuum, are unable to reach the anode, even though driven by an e. m. f. of 10,000 volts or more. The back e. m. f. due to their circular motion equals the impressed e. m. f.

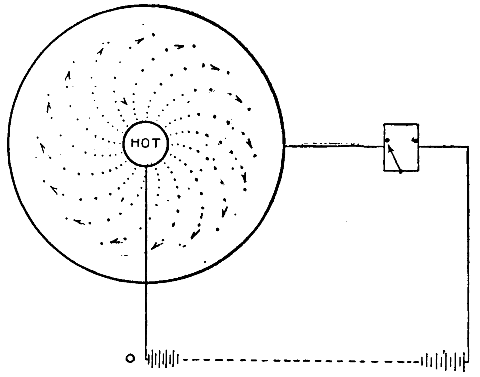

Fig. 16

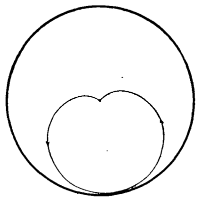

Fig. 17

The question will naturally arise, what becomes of the electrons that are thus left stranded in space? Do they return to the filament, or do they continue to circle around it forever? The answer is simple and definite. They do both. I have obtained a simple solution of their approximate paths, and Langmuir has succeeded, by approximation, in calculating the exact path. It is shown in Fig. 17 and is represented very nearly by the equation $r = R\ (\sin 2/3\ \theta)^{3/2}$ The electron flies out as near to the cylinder as it can go, depending on the strength of the magnetic field, then back to the filament, then out again, etc., *ad infinitum*, or until it strikes a gas molecule or some unsymmetrical part of the tube. The space soon becomes filled with these planets (in less than one one hundred millionth of a second, ordinarily) and their mutual repulsion prevents any more electrons from coming out of the filament.

The magnetron differs from the motor in two important respects:

1. The motion of the electrons is resistanceless and nearly inertialess, so that the back e. m. f. is established instantly when the voltage is applied, and is exactly equal to the applied voltage.
2. There is a critical value of magnetic field below which the back e. m. f. in the magnetron cannot equal a given impressed e. m. f., and the valve will not close. For all fields stronger than this critical value, it will close. This critical field is a function of the voltage, and is given by the very simple formula

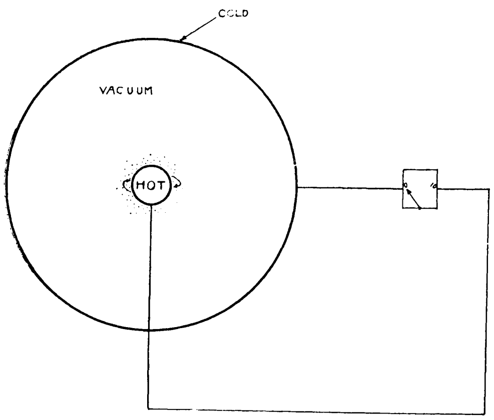

FIG. 18

$$H = \frac{\sqrt{8 \frac{m}{e} V}}{R}$$

or, putting in numerical values for m and e, the mass and charge of the electron, and expressing V, the potential across the tube, in volts, R, the radius of the external anode, in cm., and magnetic field H in lines per cm.[2],

$$H = \frac{6.72}{R} \sqrt{V}$$

COMPARISON OF THE MAGNETRON WITH OTHER "TRONS"

I have called the magnetron a *new* electric valve, for its predecessors, the kenotron rectifier, pliotron, and dynatron are all valves, each one operating on an entirely different principle and with different characteristics. The magnetron thus represents the fourth independent method of controlling the flow of current between metal electrodes in vacuum.

The *kenotron rectifier* exemplifies the control of current from one metal electrode in vacuum to another by the *temperature* of the electrodes. Electrons can pass freely from one atom to another inside a metal, so that the smallest electromotive force that can be applied is sufficient to produce a definite current. When they come to the boundary of the metal, however, and attempt to jump out into vacuum, they are held back by the attraction of the positive nuclei of the atoms, and can be pulled away only by enormous electric fields, of the order of one million volts per centimeter. A well evacuated tube, containing well rounded cold electrodes one centimeter apart, is thus a perfect insulator for voltages up to approximately one million volts.

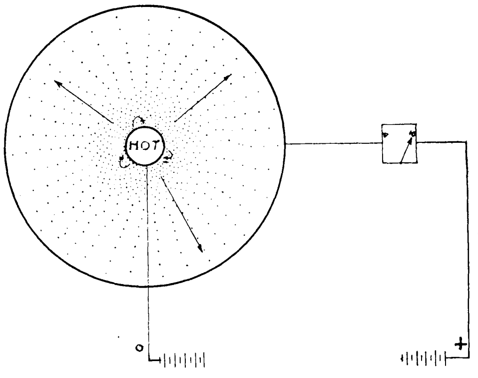

FIG. 19

When one of the electrodes is heated, however, the kinetic energy of both atoms and electrons is increased, and when sufficiently hot some of the electrons are able to jump out or evaporate, exactly as molecules evaporate from a liquid or solid. I have attempted to illustrate this in Figs. 18 and 19. The evaporating electrons drift across the vacuum to the other electrode, and constitute a unidirectional current. The rate of drift is slow, however, and they get in each other's way and cause back pressure, so that the current is very small unless they are aided by an electric field. When once out, their motion may be greatly speeded up by an electric field, and the current thus increased, precisely as evaporation of a liquid is in-

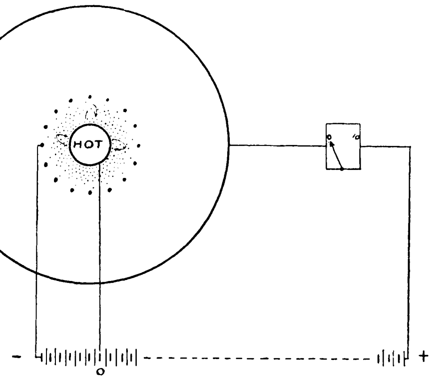

FIG. 20

creased by blowing away the vapor as fast as it is formed. Fig. 18 is intended to illustrate crudely the case of no electric field, *i. e.*, when cathode and anode are at the same potential, and Fig. 19 the case when the anode is at positive potential.

Most metals cannot be heated hot enough, without melting, to give an evaporation or "emission" of more than a few milliamperes per square centimeter. Tungsten, however, gives an emission of hundreds of amperes per sq. cm. at its melting point, and a large filament will run for years at a temperature that gives an emission of 1 amp. per cm.^{2}, or 10,000 amperes per square meter of filament surface. For example, a filament one-quarter inch in diameter and four ft. long will operate continuously for years with an emission of 225 amperes, and will operate intermittently with an emission of several thousand amperes. It is thus evident that the kenotron is capable of rectifying very large currents at high voltages.

The rate of evaporation of liquid may be limited either by its temperature or the wind velocity, according to whether or not the molecules are blown away as fast as they evaporate. In the same way the evaporation of electrons may be limited by temperature or voltage, according to whether or not the voltage is able to carry them away as fast as they evaporate. When they are not carried away as fast as they jump out, they pile up in the space around the hot filament and produce a back pressure on those that are trying to follow, forcing them back into the filament. This condition is generally referred to as " space charge limitation"; *i. e.*, limitation of the current of oncoming electrons by the electrostatic repulsion of the electrons present in the space between the electrodes.

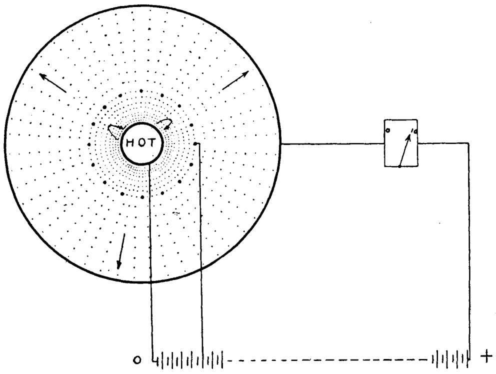

FIG. 21

I have emphasized the idea of *space charge* because it is the principle of operation of the *pliotron*,—the second method of control. In the pliotron the current that can flow from a hot filament to a cold anode is controlled by a grid interposed between filament and plate. The grid acts as an electrostatic screen, shielding the filament from the positively charged anode. The filament temperature is maintained high, so that the current is limited only by space charge, and the space charge limitation is determined by the potential of the grid.

This is roughly illustrated by Figs. 20 and 21. In Fig. 20 the grid is at a negative potential with respect to the filament, and repels the electrons so that they pile up around the filament and prevent any current flow. The valve is closed. In Fig. 21 the grid is positive, and pulls the evaporating electrons away at a sufficient rate to give a large current. The valve is open. Although it is the grid potential that pulls the electrons away from the filament, most of them go through between the grid wires to the anode, and very few strike the grid. Very little energy is, therefore, needed to open and close the valve. The pliotron is an efficient valve.

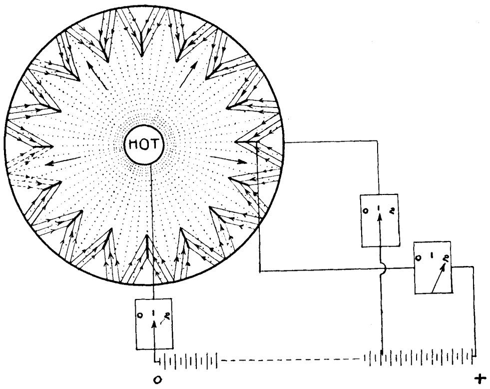

FIG. 22

The third method of control is exemplified by the *dynatron*, and illustrated in Fig. 22. I have explained that electrons cannot be pulled out of a cold metal except by very intense electric fields. They may, however, be *splashed* out by the impact of high-speed electrons on the metal. Each impinging electron may splash out from one to five or more secondary electrons, depending on the speed of impact. The secondary electrons may flow to a more positive anode (in Fig. 22 a grid) and thence through a work circuit; or power may be derived from the secondary cathode or "dynode" itself, since it has the characteristic of a

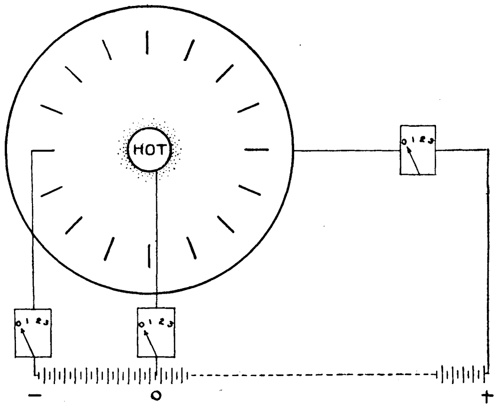

FIG. 23

negative resistance.[1] The production of secondary electrons may be controlled by varying the number and speed of the impinging electrons, and thus the dynatron valve may be opened or closed to any desired degree. The impact excitation of electrons has the advantage over temperature in that it may be turned on or off instantly, while time is required to heat or cool a filament.

The fourth method of control is exemplified by the *magnetron*, as illustrated by Figs. 15 and 16. The electrons try to fly straight across from filament to anode. Since they are moving in a magnetic field, they are acted on by a mechanical force equal, in direction and magnitude, to the vector product of their velocity and the magnetic field. This causes them to move in curved paths as shown in Fig. 15. They all strike the anode, in spite of the curvature, as long as the magnetic field strength is below a certain critical value, as in Fig. 15. The valve is wide open. If the magnetic field is above this critical value as in Fig. 16, none of them strike. The valve is closed.

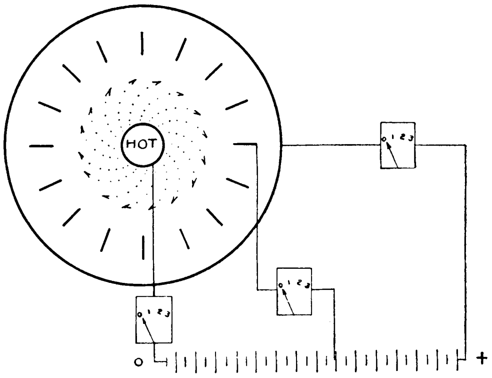

FIG. 24

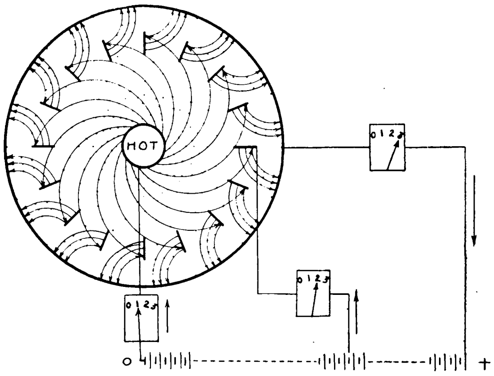

FIG. 25

These four methods of control of current flow in vacuum may be summarized by saying that two of them have to do with getting the electrons out of the metal into vacuum, by *boiling* and *splashing* respectively; the other two with controlling their flow after they are out, by means of *back e. m. f. produced electrostatically and electromagnetically* respectively.

These different methods of control may be combined in the same tube in many different ways. An example is given in Figs. 23, 24 and 25. A work circuit is to be assumed connected externally between grid and anode, and a uniform magnetic field at right angles to the plane of the figure. In Fig. 23 the filament is hot; that is, the primary valve is open; but the electrons are prevented from escaping by the back e. m. f., due to the negative potential impressed on the grid. In Fig. 24 the grid is positive, trying to drag the electrons from the filament, but they are prevented from getting as far as the grid by the back e. m. f., due to their motion in the magnetic field. In Fig. 25 the grid is sufficiently positive so that all the electrons strike it in spite of the magnetic field. These electrons are stopped by the grid. If they strike it with low velocity, that is, if the grid is only a few volts positive, they will produce very few secondary electrons, and hence very little current will flow to the anode. The valve will still be closed. In Fig. 25 the grid potential is assumed to be sufficiently positive so that the impact of the primary electrons on it gives rise to a large number of secondary electrons. These are free to flow across to the anode and thence through the work circuit. The valve is open. It should be noted that, in order to open this valve, all four controls must be open at once—any one of them is sufficient to close the valve.

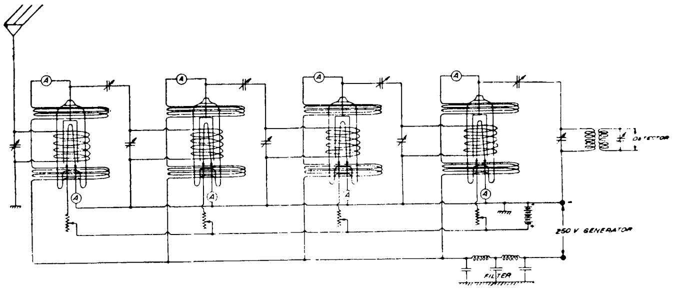

FIG. 26

APPLICATIONS

In conclusion I will say just a word about applications. The magnetron is so young that its applications are mostly hopes. The only purpose for which it is actually being used is as "synchronous detector" in continuous wave radio telegraphy, in the transoceanic receiving stations of the Radio Corporation.[2] In this case the magnetron acts as a simple high-frequency valve, opened and closed at approximately signal frequency by a locally generated magnetic field, letting

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[1] For description of the dynatron see *Proc.* Inst. Radio Eng., Vol. 6, pp. 5-36, Feb. 1918.

[2] The synchronous detector will be described eleswhere by its inventor, Mr. E. F. W. Alexanderson.

through first the positive peaks of the signal and then the negative, giving an audible tone.

We have experimented with magnetrons as amplifiers, the current to be amplified being used to energize the magnetic field, and the output circuit being in series with the tube and battery. The operation is about the same as that of the pliotron, and the degree of amplification about the same. In a four-tube radio frequency amplifier we obtained fivefold current amplification per stage The circuit is shown in Fig. 26. In these tests the magnetrons used somewhat larger currents than pliotrons, but this is a question of tube and circuit development. The two methods of control are very similar, the pliotron utilizing for control the potential difference at the terminals of a coil, the magnetron the magnetic field of the same coil; and it appears that the amount of control obtained is about the same in the two cases.

We have also made tests with magnetrons as generators of high-frequency alternating current. The tube shown in Fig. 1, which has an anode 4 in. in diameter by 12 in. long, has been operated with an output of 5 kw. of high-frequency power, and is capable, with proper development of the circuit, of 25 kw. output. The circuits used are shown in Figs. 27 and 28.

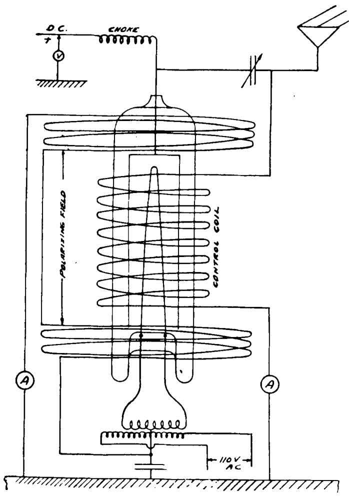

FIG. 27

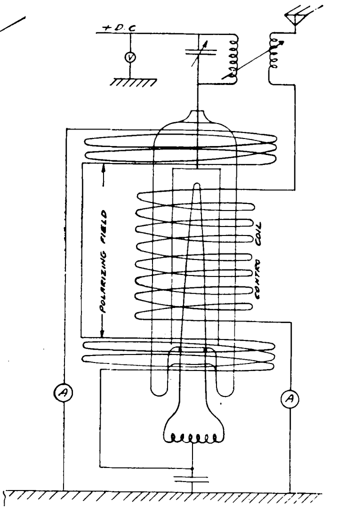

FIG. 28

It is thus possible that the magnetron will find applications in the radio field. It has the advantage of cheap construction, and of separating the input and output circuits. Its most probable service in this field is in combination with other methods of control. The tube shown in Figs. 23-25 is by far the most efficient oscillator we have tried.

The field of radio is insignificant, however, compared with that of engineering, and it is in engineering that vacuum tubes will find their most important applications.

One of these applications is the use of magnetrons as lightning and surge arresters. The magnetron is connected in multiple with the machine to be protected, and the magnetic field is adjusted so that no current flows through the magnetron under normal conditions. If the voltage rises above normal, however, as soon as it reaches a definite predetermined excess the magnetron valve opens wide, allowing very large current to flow, but closes again as soon as the voltage falls below this same value. The time lag in the tube is nearly zero, manifold smaller than in the sphere gap, and the magnetron may find applications where this speed is important. Fig. 29 shows a simple application in which a magnetron is used to protect a high-voltage d-c. line.

I have pointed out some of the applications for which the magnetron is especially adapted. There are many other applications for which vacuum tubes are suitable, and for which one may confidently predict they will be used. Their capacity is ample. The tube shown in Fig. 1 is capable, with larger filament and water cooling, of handling hundreds of amperes at almost any voltage used in engineering. One may predict that one year will see these tubes in use as kenotron rectifiers for series arc lighting. Five years will see them in substations replacing synchronous converters. In ten years they will be on electric locomotives, either as rectifiers, allowing the use of d-c. motors, or as variable frequency alternators, taking their power from a high-tension d-c. trolley line. Twenty years will see d-c. transmission lines, fed through transformers and kenotrons, at any convenient points, by alternators of any frequency, and tapped by the same tubes acting as magnetron alternators, or some equivalent pliotron or combination vacuum-tube alternator.

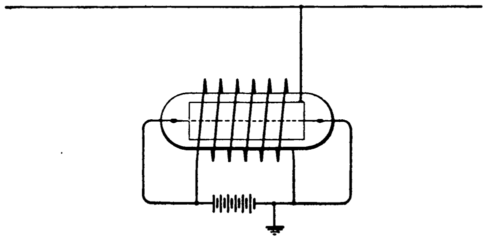

FIG. 29

The power capacity of tubes is ample for these purposes. Electron devices are not small inherently; they are only young.