July 8, 1969 KENICHI OWAKI ET AL 3,454,824

NON-UNIFORM MAGNETIC FIELD MAGNETRON DEVICE

Original Filed Feb. 24, 1965 Sheet 1 of 2

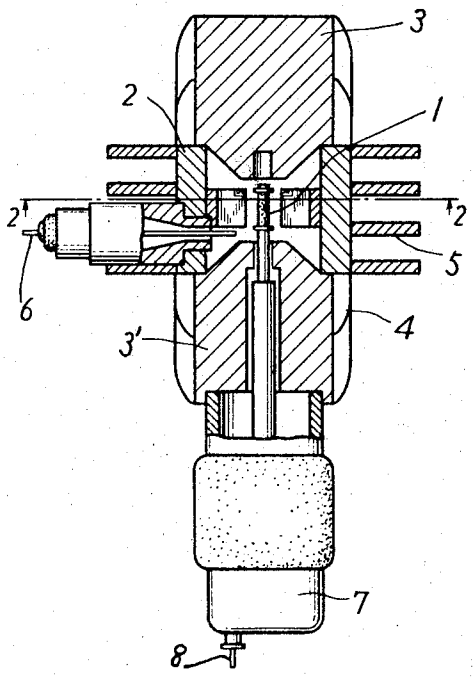


Fig. 1

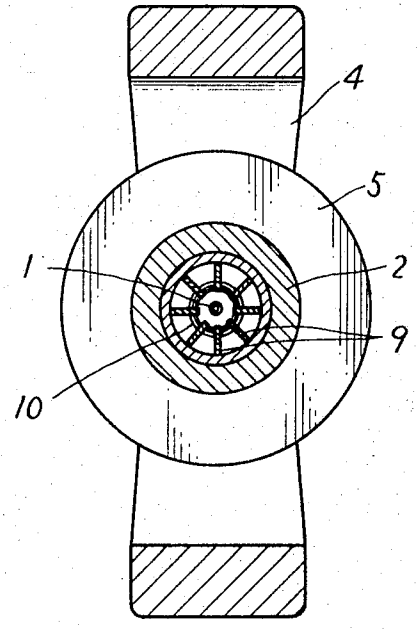


Fig. 2

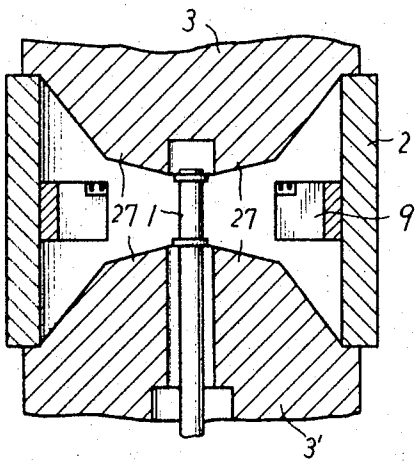


Fig. 6

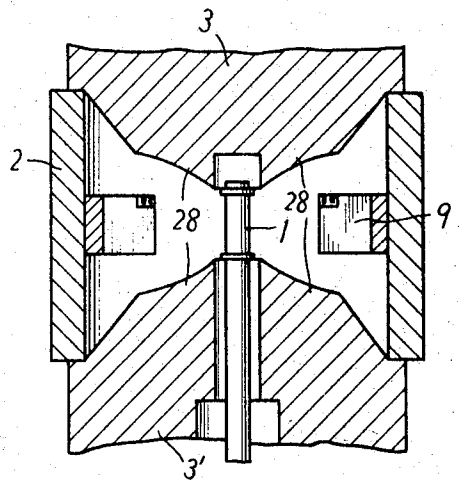


Fig. 7

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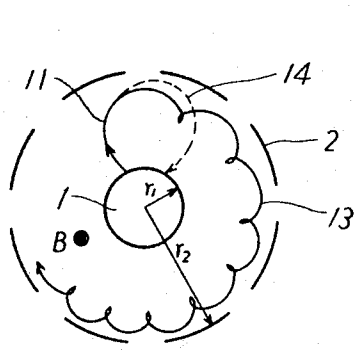


Fig. 3

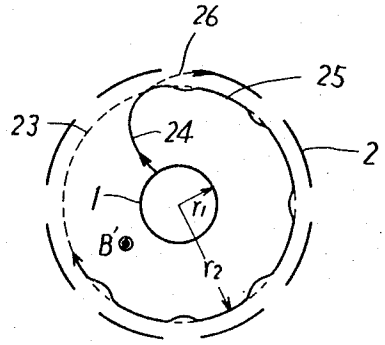


Fig. 5

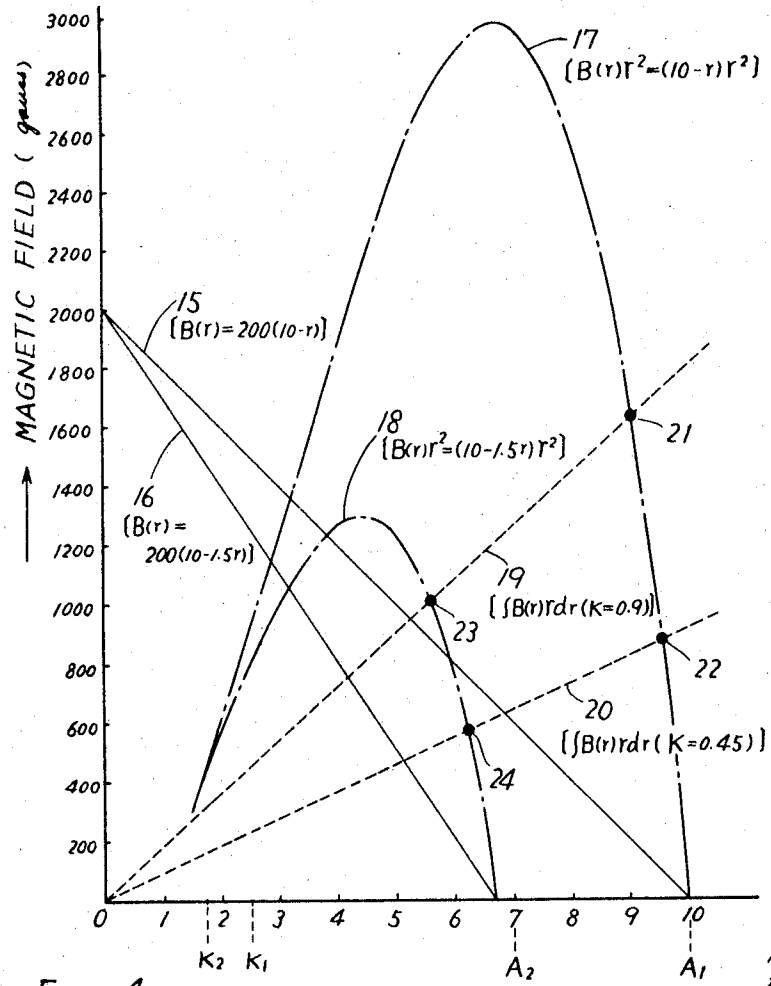


Fig. 4

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NON-UNIFORM MAGNETIC FIELD MAGNETRON DEVICE

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Continuation of application Ser. No. 434,811, Feb. 24, 1965. This application Feb. 27, 1968, Ser. No. 708,538

Int. Cl. H01j 25/50

U.S. Cl. 315—39.71

4 Claims

ABSTRACT OF THE DISCLOSURE

An improved magnetron wherein the magnetic and electric fields are correlated to provide a stable electron path, the magnetic field satisfying the betatron "2 for 1 rule."

This invention is a continuation of United States patent application Ser. No. 434,811, now abandoned filed Feb. 24, 1965, entitled Non-Uniform Magnetic Field Magnetron Device.

This invention relates to magnetrons and more particularly to a novel and improved magnetron characterized by its dependability and substantially increased life.

The magnetron, while having numerous advantages, such as high efficiency, large output power, and relatively small size, does have limited life caused by certain opearting characteristics of the tube. As is well-known, the magnetron operates to emit electrons from its cathode under the influence of both an electric field and a magnetic field which cause the electrons to form what may be termed a rotating cloud or movement in space. This action causes the generation of a strong, super high-frequency oscillation, the frequency of which being determined by the characteristics of the tube. In the operation of the conventional magnetron, electrons which are emitted from the cathode under the influence of both the direct current electric field between the cathode and the anode and the high frequency field produced by the anode as a result of the oscillation causes the electrons to be decelerated and these electrons function to promote the oscillation. A portion of the electrons, however, absorb the high frequency energy and are accelerated in such a manner that they return to and impinge upon the cathode and cause overheating of the cathode. This overheating phenomenon as a result of returning electrons is generally called "back-heating." Efforts have been made to utilize back-heating as a heat source for the cathode, but it has been found that back-heating generally results in a material shortening of the life of the cathode. This phenomenon is perhaps one of the most undesirable disadvantages of the conventional magnetron.

One object of this invention resides in the provision of a novel and improved magnetron wherein back-heating is eliminated without adversely affecting the efficiency of the tube.

Another object of the invention resides in the provision of a novel and improved magnetron characterized by its long life and high efficiency.

The foregoing objects are achieved in accordance with the invention by providing a magnetron with a magnetic field in the interelectrode space which is of non-uniform character. The use of a non-uniformly distributed magnetic field and a specific electric field coordinated with the magnetic field forms a stable track or path for the movement of the electrons. As a result, any accelerated electrons which heretofore caused back-heating will depart from the stable path and strike the anode.

While many efforts have been made to eliminate back-heating and other difficulties through the control of magnetic fields, such methods have not been effective in minimizing back-heating with the result that little, if any, improvement was obtained over the conventional magnetron utilizing the uniform magnetic field.

This invention embodies the concept of the development of a stable path within the magnetron for movement of the electrons, and it has been confirmed by actual experiment that a stable path can be produced by properly coordinating the electric and magnetic fields. As mentioned above, the utilization of a stable path in the magnetron prevents back-heating and thus enables the production of a magnetron having long life as well as the high efficiencies of the conventional magnetron.

The above and other objects of the invention will become more apparent from the following description and accompanying drawings forming part of this application.

In the drawings:

FIGURE 1 is a side elevational view in partial section of a conventional magnetron.

FIGURE 2 is a cross-sectional view of the conventional magnetron shown in FIGURE 1.

FIGURE 3 is a diagram showing the movement of electrons in the conventional magnetron.

FIGURE 4 is a graph illustrating a method for producing a stable path of electrons in a magnetron in accordance with the invention.

FIGURE 5 is a diagram of the movement of electrons in a magnetron in accordance with the invention.

FIGURES 6 and 7 are fragmentary cross-sectional views of the principal portions of two forms of magnetrons in accordance with the invention.

Reference is now made to the drawings and more specifically to FIGURES 1 through 3 which have been included for the purpose of explaining the structure and operation of a conventional magnetron. In these figures, the numeral **1** denotes the heated cathode which is surrounded by an anode structure **2**. The magnetic poles are denoted by the numerals **3** and **3'**, and flux is generated between the pole pieces by a surrounding permanent magnet **4**. The anode **2** includes a plurality of cooling fins **5** and energy is obtained from the magnetron by means of the output terminal **6**. The heater for the cathode **1** is connected through suitable leads to the terminals **7** and **8** on the bottom of the magnetron.

The anode **2** is shown more clearly in FIGURE 2, and it will be seen that it includes eight inwardly extending radially disposed fins **9** which are secured at their outer ends to the anode sturcture **2**. A pair of straps **10** each connect alternate anode fins **9** within the tube.

For convenience in explaining the operation of the magnetron shown in FIGURES 1 and 2, a graphical display is provided in FIGURE 3. The cylindrical anode **2** is represented by the broken circle, and the number of gaps in the circle corresponds to the number of anode fins **9**. The space between the cathode **1** and the broken circle **2** representing the anode forms the interelectrode space. When the cathode is heated, electrons emerge from the surface of the cathode as generally represented by the solid line **11**. The path of the electrons is curved by the action of the magnetic field B which is essentially perpendicular to the surface of the paper. As a result of the influence of the exceedingly high frequency field which is produced in the gaps of the anode **2**, the electrons are decelerated and move in an oscillatory path denoted by the solid line **13** and thus function to promote oscillation. These electrons ultimately strike the anode **2**. As pointed out above, other electrons emitted from the cathode **1** are in fact accelerated by the very high frequency electric field, thereby increasing their

kinetic energy and causing them to move in a large arc as indicated by the dotted line **14**. These electrons in moving through the arc **14** return to and impinge on the cathode and cause substantial back-heating. It is to be understood that in conventional magnetrons the magnetic field B is uniform throughout the interelectrode space.

The instant invention involves the utilization of a non-uniform magnetic field in the interelectrode space having a distribution such that $B=B(r)$ where r is the radial distance from the center of the magnetron. Furthermore, the distribution of the magnetic field must be such that, when it is combined with the interelectrode electric field, the nature of the distributed magnetic field must satisfy a condition corresponding to that of the so-called "betatron" stable orbit, the betatron "2 for 1 rule," in which case all of the electrons emitted from the cathode will converge into said path and continue in a stable circular movement.

The following derivation explains the betatron "2 for 1 rule."

From Faraday's law of electromagnetic induction

$$\epsilon+\frac{1}{c}\frac{d\varphi}{dt} \tag{1-1}$$

According to Ampere's law

$$\vec{F}=e\frac{\left(\vec{v}\times\vec{B}\right)}{c} \tag{1-2}$$

Applying Newton's law to the radial force results in the following equation:

$$\frac{evB(r_0)}{c}=\frac{mv^2}{r_0}=Ma \tag{1-3}$$

$$mv=\frac{er_0B(r_0)}{c} \tag{1-4}$$

Thus Equation 1–4 gives the tangential momentum required for the electrons to orbit at radius r_0 under magnetic field $H(r_0)$.

Applying Newton's law to the tangential force, it is found that:

$$\vec{e\Delta\epsilon}=\frac{e}{2\pi r_0c}\frac{d\varphi}{dt}=\frac{d(mv)}{dt} \tag{1-5}$$

where ϕ is the flux within the circumference of the circle of radius r_0. Integrating from $\phi=0$ and $mv=0$, it is found that:

$$mv\frac{e\varphi}{2\pi r_0c} \tag{1-6}$$

Equation 1–6 gives the tangential momentum gained by an electron moving from the center out to the orbit distance r_0. If the momentum given by (1–4) is equal to that given by (1–6), then the electrons will continue to orbit at radius r_0. Thus setting (1–4) and (1–6) equal, the condition for the magnetic field required for a stable orbit is found below.

$$\frac{er_0B(r)_0}{c}=\frac{e\varphi}{2\pi r_0c} \tag{1-7}$$

$$\varphi=2\pi r_0^2B(r_0) \tag{1-8}$$

By definition:

$$\varphi(r_0)=\int_0^{r_0}B(r)2\pi rdr \tag{1-9}$$

where ϕ is all of the flux within the circle of radius r_0.

Then

$$\varphi(r_0)=\int_0^{r_0}B(r)2\pi rdr=2\pi r_0^2B(r_0) \tag{1-10}$$

and

$$\varphi(r_0)\int_0^{r_0}B(r)rdr=r_0^2B(r_0) \tag{1-11}$$

Equation 1–11 is the betatron "2 for 1 rule." By way of clarafication assume that $B(r)$ is a constant, $B_{(average)}$ then

$$\varphi=\frac{B_{(average)}r_0^2}{2}=r_0^2B(r_0) \tag{1-12}$$

and

$$B_{(average)}=2B(r_0) \tag{1-13}$$

Thus it is seen that the average magnetic field from 0 to r_0 is equal to twice the field at r_0. Therefore the designation "2 for 1 rule" is utilized.

Solution of the general equations of motion for an electron in a magnetic and electric field make clear the use of the betatron "2 for 1 rule" and the voltage requirements for this device. These equations for the magnetic field $B(r)$ directed in the negative Z direction and an electric field $E(r)$ directed radially inward are given in cylindrical co-ordinates by

$$m\left[\frac{dr^2}{dt^2}-r\left(\frac{d\theta}{dt}\right)^2\right]=eE(r)-eB(r)r\frac{d\theta}{dt} \tag{2}$$

$$m\frac{d}{dt^2}\left(r^2\frac{d\theta}{dt}\right)=eB(r)r\frac{dr}{dt} \tag{3}$$

When $t=0$, integration of Equation 3 using the initial conditions $r=r_1$ and $d\theta/dt=0$ gives

$$r^2\frac{d\theta}{dt}=\frac{e}{m}\int_{r_1}^{r}B(r)rdr \tag{4}$$

Equation 4 is substituted into Equation 2 giving

$$\frac{d^2r}{dt^2}=\frac{e}{m}E(r)-\left(\frac{e}{m}\right)^2\frac{Br}{r}\int_{r_1}^{r}B(r)rdr+\left(\frac{e}{m}\right)^2\frac{1}{r^3}\left[\int_{r_1}^{r}B(r)rdr\right]^2 \tag{5}$$

Now the potential between two concentric cylindrical surfaces, the inner one of radius r_1 and the outer one of radius r_2, is given by the following equation:

$$V(r)=V_0\frac{\ln r-\ln r_1}{\ln r_2-\ln r_1} \tag{6}$$

The energy of the electron after falling through a potential of $V(r)$ is given by

$$eV(r)=\frac{m}{2}\left[\left(\frac{dr}{dt}\right)^2+r^2\left(\frac{d\theta}{dt}\right)^2\right] \tag{7}$$

Substituting Equation 4 and Equation 6 into Equation 7 gives

$$\frac{1}{2}\left(\frac{dr}{dt}\right)^2=\frac{e}{m}\frac{V_0\ln(r/r_1)}{\ln(r_2/r)}-\left(\frac{e}{m}\right)^2\frac{1}{2r^2}\left[\int_{r_1}^{r}B(r)rdr\right]^2 \tag{8}$$

A stable orbit at radius $r=r_0$ will be obtained when the conditions $d^2r/dt^2=0$ and $dr/dt=0$ at $r=r_0$ are satisfied. If these conditions are met, Equation 8 becomes

$$V_0\frac{\ln(r_0/r_1)}{\ln(r_2/r_1)}=\frac{1}{2}\frac{1}{r_0^2}\frac{e}{m}\left[\int_{r_1}^{r_0}B(r)rdr\right]^2 \tag{9}$$

Equation 9 is the condition which the voltage must satisfy. It can be rewritten as

$$\int_{r_1}^{r_0}B(r)rdr=\sqrt{\frac{2mV_0}{e}\frac{\ln(r_0/r_1)}{\ln(r_2/r_1)}}r_0 \tag{10}$$

Now $E(r)=\partial V/\partial r$ which applied to Equation 6 gives

$$E(r)=-\frac{V_0}{\ln r_2/r_1}\frac{1}{r} \tag{11}$$

Application of the boundary condition $d^2r/dt^2=0$ at $r=r_0$ and to Equation 5 plus substitution of Equation 11 gives

$$\frac{V_0}{\ln(r_2/r_1)}\frac{1}{r_0}+\frac{e}{m}\frac{B(r_0)}{r_0}\int_{r_1}^{r_0}B(r)rdr=\frac{e}{m}\frac{1}{r_0^3}\left[\int_{r_1}^{r_0}B(r)rdr\right]^2 \tag{12}$$

From Equation 9 the following can also be obtained.

$$V_0=\frac{1}{2r_0^2}\frac{\ln (r_2/r_1)}{\ln (r_0/r_1)}\frac{e}{m}A^2 \qquad (13)$$

where

$$A=\int_{r_1}^{r_0}B(r)rdr$$

Substitution of this into Equation 12 gives

$$\frac{1}{2r_0^3\ln (r_0/r_1)}\frac{e}{m}A^2+\frac{e}{m}\frac{B(r_0)}{r_0}A=\frac{e}{m}\frac{1}{r_0^3}A^2 \qquad (14)$$

Equation 14 reduces to

$$\frac{1}{2\ln (r_0/r_1)}A+B(r_0)r_0^2=A \qquad (15)$$

Equation 15 becomes

$$B(r_0)r_0^2=\left(1-\frac{1}{\ln (r_0/r_1)^2}\right)\int_{r_1}^{r_0}B(r)rdr \qquad (16)$$

In the present embodiment of the invention, Equation 16 becomes the exact criteria for the magnetic field. However, if r_1, the radius of the cathode is made small enough, the term

$$\left(1-\frac{1}{\ln (r_0/r_1)^2}\right.$$

approaches 1 and the required magnetic field distribution is given by the "2 for 1 rule"; that is it becomes

$$B(r_0)r_0^2=\int_{r_1}^{r_0}B(r)rdr \qquad (17)$$

For practical applications this criteria is sufficient.

Thus it is found that the radius of the stable track or path is a value which is related to the anode voltage V of the magnetron, the log r_2/r_1 (the ratio of the radii of the anode and the cathode), the mass m of the electrons, and the electric charge e (Equation 10). The value determined by the various dimensions set forth in Equation 10 is assumed to be a proportional constant K. Thus by selection of the value K (selection of V, r_1 and r_2) the radius of the stable track or path can be chosen as desired. In practice it is preferable that the stable path is properly chosen close to the anode.

FIGURE 4 illustrates the manner in which the stable path is determined utilizing the foregoing theory and the fact that the stable track or path that actually exists. The absicissa in FIGURE 2 represents the distance r from the center of the magnetron, and the ordinate represents the magnetic field intensity.

Example 1

If the center of the magnetron is $r=0$ and assuming a magnetic field intensity of 2000 gauss and a magnetic field distribution which varies in accordance with the function $B(r)=2000\ (10-r)$ gauss in the radial direction, then the magnetic field distribution $B(r)$ is represented by the straight line 15, and $B(r)\cdot r^2$ is represented by the curve **17**. Furthermore, the function $\int B(r)\cdot r\cdot dr$ when $K=0.45$ (the anode radius $r_2=10$ mm., the cathode radius $r_1=2.5$ mm., and the anode voltage is 3 kv.) defines the straight line **20**. The magnetic field distribution satisfying Equation 5 is determined by the crossing point **22** of the line **20** with the curve **17**. This point indicates that the stable track or path is at a place where the radius is equal to 9.6 mm.

Example 2

When the distribution of the magnetic field is the same as in Example 1 and if the anode voltage and the electrode radii are chosen so that $K=0.9$, the function $\int B(r)\cdot r\cdot dr$ defines the straight line **19**. This line crosses the curve **17** at the point **21** and will produce a stable track or path in the position where $r=9.1$ mm.

Example 3

In the case of a magnetron wherein the magnetic field intensity at $r=0$ is 2000 gauss and the magnetic field distribution $B(r)=2000(10-1.5r)$ gauss, the distribution is then represented by the straight line **16** and $B(r)r^2$ defines the curve **18**. The curve **18** crosses the lines **19** and **20** at points **23** and **24** respectively. The stable tracks or paths are therefore formed at positions of 5.5 mm. and 6.2 mm. from the center of the magnetron respectively.

The illustration in FIGURE 5 explains the movement of the electrons of a magnetron in accordance with the invention which has a stable track or path determined by the aforementioned equation. In this figure, the numeral **1** denotes the cathode, **2** denotes the anode and **23** denotes the stable track or path. Electrons emitted from the cathode **1** move outwardly toward the anode through a curved path **24** determined by the combined effects of the non-uniform magnetic field in the interelectrode space and the electric field. Inasmuch as the magnetic field and electric field are determined in accordance with Equation 5 all of the electrons will move into the stable track or path **23** provided however that there is no super high-frequency electric field in the gaps of the anode. Under conditions wherein the super high-frequency electric field does exist, the electrons which are decelerated by the electric field are deprived of energy by the anode circuit, and as a result, they tend to depart slightly toward the inside of the stable track as indicated by the solid line **25** and thus contribute to the oscillation. Those electrons after losing sufficient energy are then attracted by the anode. Electrons, which are accelerated by the electric field, obtain a large quantity of kinetic energy and in so doing they move outwardly of the stable track as indicated by the dotted line **26** whereupon they strike the anode **2** and do not return to the cathode. Thus back-heating is prevented.

FIGURES 6 and 7 are two forms of a magnetron structure in accordance with the invention. In FIGURE 6, the effective end faces of the magnetic poles **3** and **3'** are provided with inclined or conical faces **27** and thereby produce a non-uniform magnetic field in the interelectrode space through which the electrons rotate. In FIGURE 7, the pole pieces **3** and **3'** are provided with inwardly curved faces **28** which, while providing a non-uniform magnetic field as in the structure of FIGURE 6, provide such a field with a different flux distribution. Thus in the design of a magnetron in accordance with the invention, the particular configuration of the faces of the pole pieces would be selected to provide a stable path or track at the desired distance from the center of the tube.

Except for the configuration of the pole pieces by which non-uniform magnetic fields of predetermined distributions are obtained, the structural elements of the magnetron in accordance with the invention are essentially the same as those of conventional magnetrons.

While only certain embodiments of the invention have been illustrated and described, it is apparent that alterations, modifications and changes may be made without departing from the true scope and spirit thereof as defined by the appended claims.

What is claimed is:

1. A non-uniform magnetic field magnetron device comprising a cathode having a central axis, a concentric anode surrounding said cathode, terminal means on said cathode and anode for applying a direct current potential therebetween, and means for producing a non-uniform magnetic field in the space between said cathode and anode and in the direction of the axis of the cathode, said magnetic and electric fields satisfying the following equation:

$$\int_{r_1}^{r_0}B(r)\cdot r\cdot dr=\sqrt{\frac{2mV_0}{e}\frac{\ln (r_0/r_1)}{\ln (r_2/r_1)}}\,r_0$$

and said magnetic field varying as a function of the radial distance from the axis of said cathode and satisfying the following equation:

$$\int_{r_1}^{r_0} B(r)\cdot r\cdot dr = B(r_0)\cdot r_0^2$$

wherein:

e is an electric charge of electrons,
m is a mass of electrons,
V is a voltage between said cathode and said anode,
r_1 is the radius of said cathode,
r_0 is the orbiting radius, and
r_2 is the inner radius of said anode.

2. In a magnetron having a cathode, an annular anode surrounding said cathode and spaced therefrom to form an interelectrode space therebetween, a magnetic pole on each side of said anode, said poles for producing a magnetic field in said interelectrode space and passing between said cathode and anode, said poles having end faces shaped to form an annular gap therebetween with the width of the gap in the vicinity of the cathode being a minimum and in the vicinity of the anode being a maximum, said poles producing a non-uniform magnetic field in accordance with the betatron "2 for 1 rule."

3. In a magnetron according to claim **2** wherein the width of the gap increases uniformly.

4. In a magnetron according to claim **2** wherein the width of said gap increases non-uniformly.

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U.S. Cl. X.R.

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