April 18, 1967 CHAO CHEN WANG 3,315,110

SHAPED-FIELD HOLLOW BEAM ELECTRON GUN HAVING HIGH BEAM PERVEANCE AND HIGH BEAM CONVERGENCE RATIO

Filed Aug. 12, 1963 4 Sheets-Sheet 1

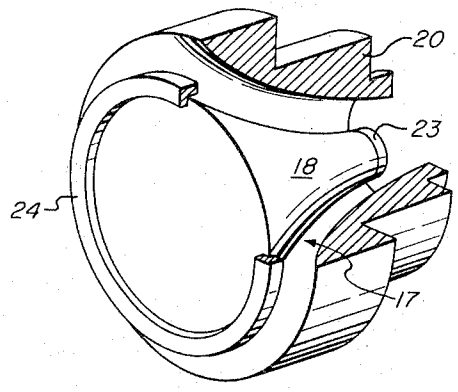


FIG. 1.

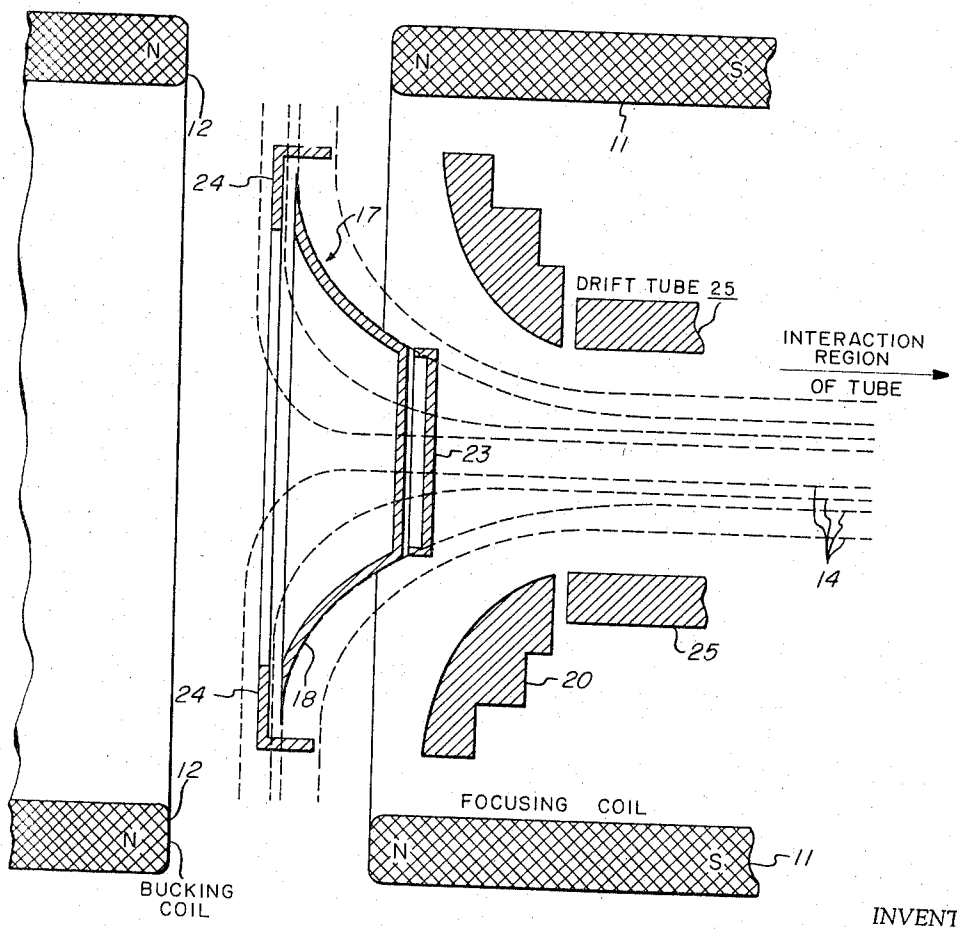


FIG. 2.

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4 Sheets-Sheet 2

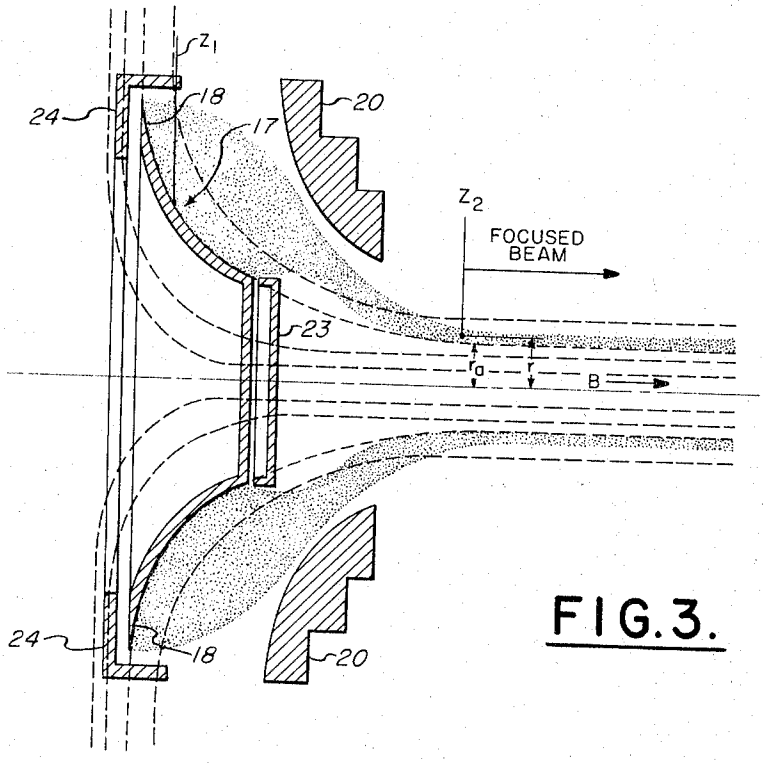


FIG.3.

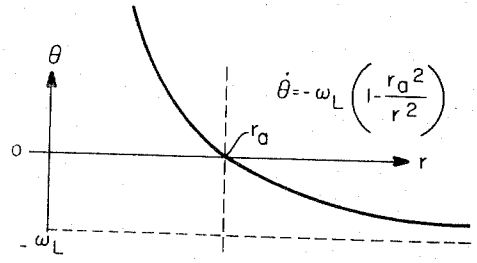


FIG.4.

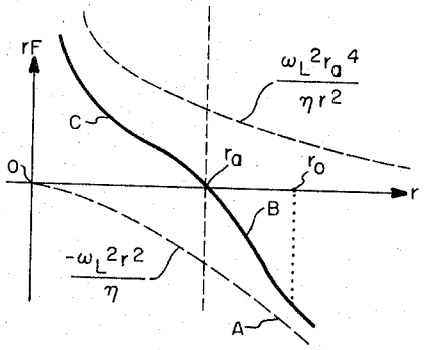


FIG.5.

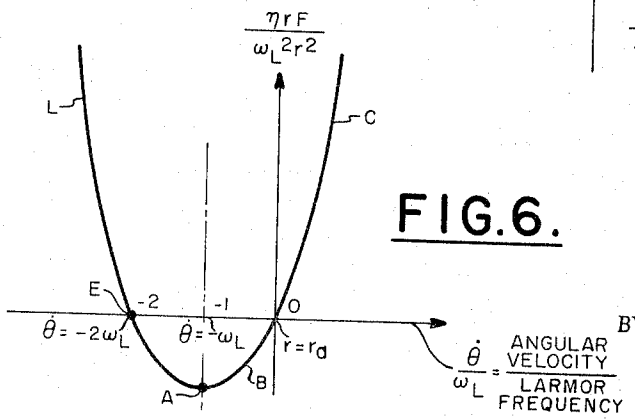


FIG.6.

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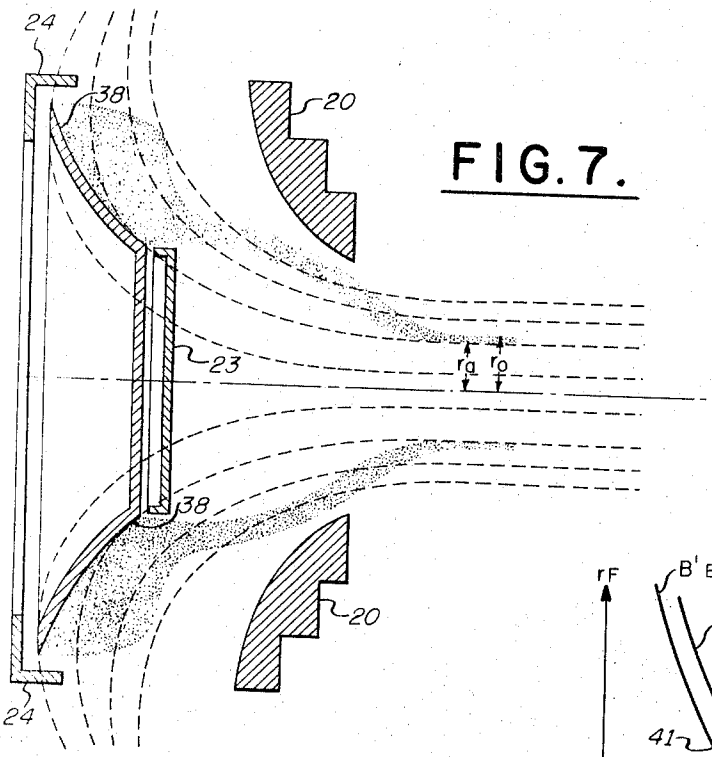


FIG. 7.

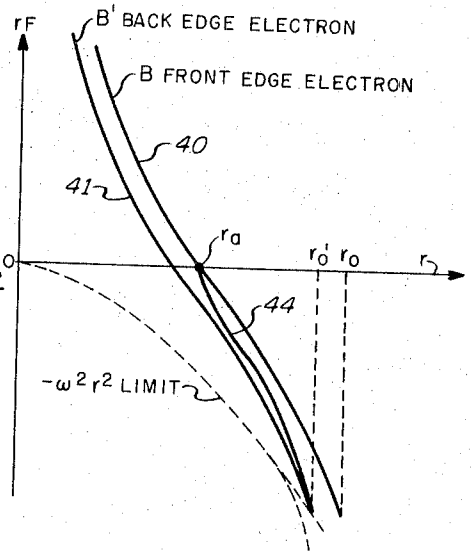


FIG. 8.

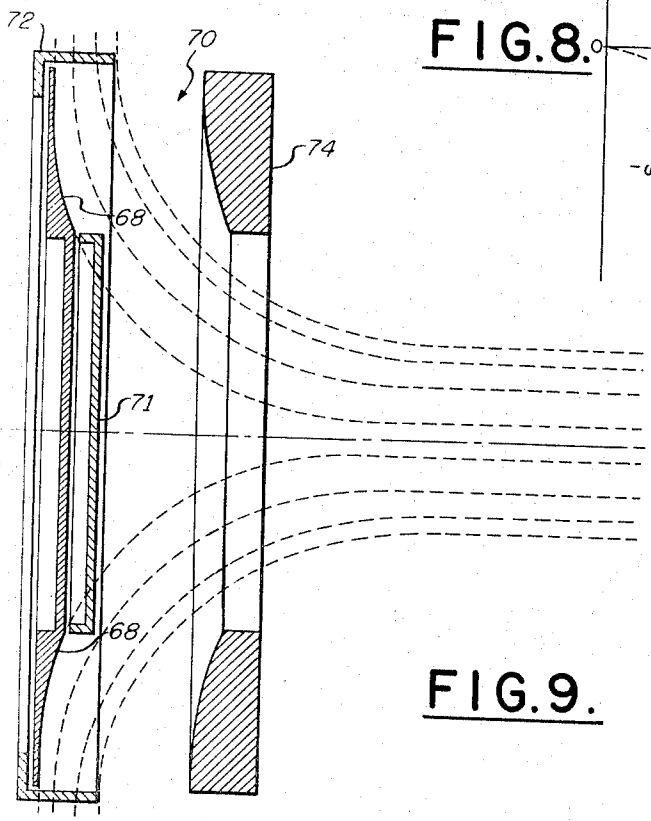


FIG. 9.

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SHAPED-FIELD HOLLOW BEAM ELECTRON GUN HAVING HIGH BEAM PERVEANCE AND HIGH BEAM CONVERGENCE RATIO

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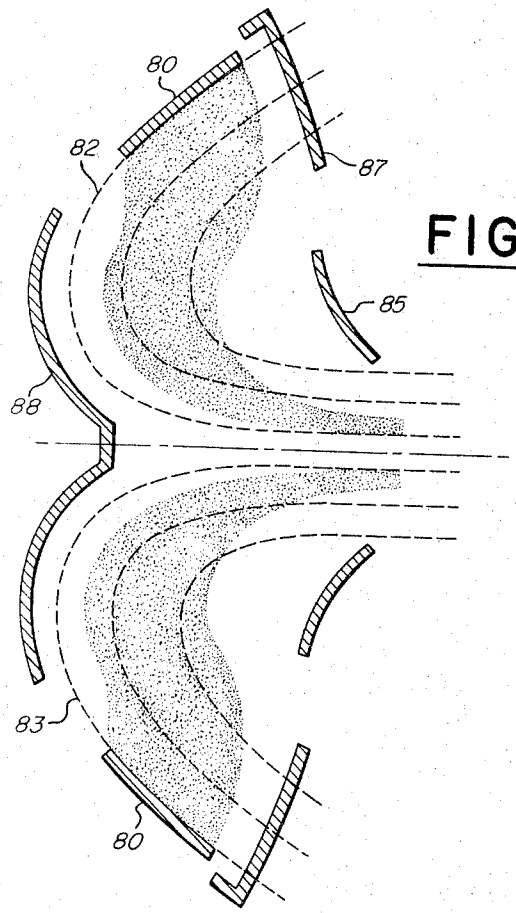


FIG.10.

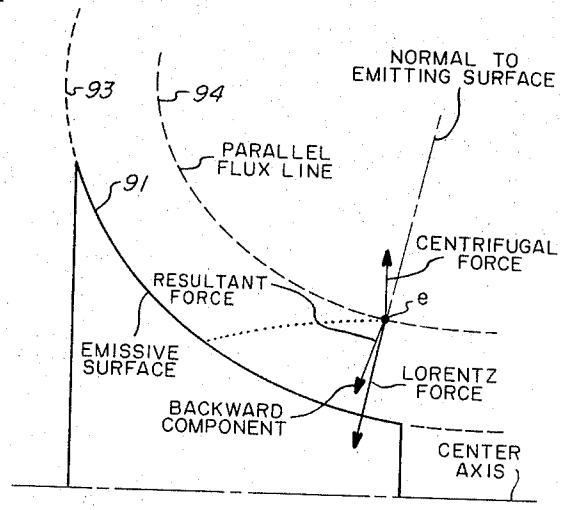


FIG.11.

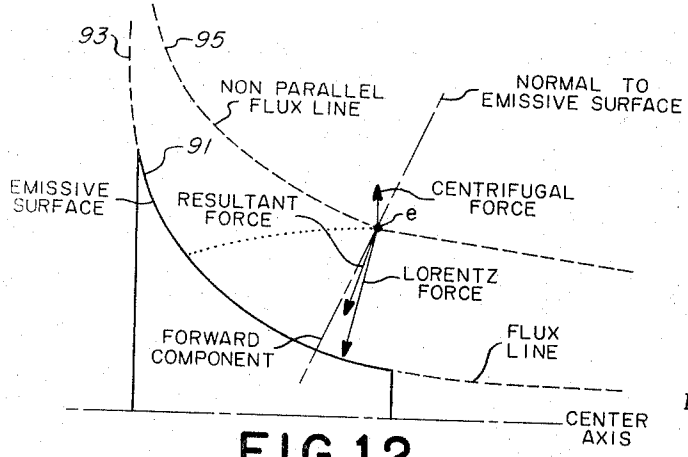


FIG.12.

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3,315,110

SHAPED-FIELD HOLLOW BEAM ELECTRON GUN HAVING HIGH BEAM PERVEANCE AND HIGH BEAM CONVERGENCE RATIO

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Filed Aug. 12, 1963, Ser. No. 301,368
15 Claims. (Cl. 313—84)

This invention relates to an electron beam gun for producing a hollow electron beam having high perveance, high convergence ratio, and a low noise figure.

Most of the klystron and traveling wave tubes presently in operation employ a solid pencil electron beam that is coupled to electromagnetic waves supported on a suitable standing wave or traveling wave structure. It has been found that the solid electron beams have serious limitations when employed in tubes intended to operate at high power levels and/or high frequencies. These limitations result from the fact that the space charge forces in the solid beam limit the current obtainable in a well focused beam, for a given operating voltage, thus limiting the power output obtainable with such a solid beam. Additionally, the electromagnetic waves interact only with those electrons in the outer regions of the beam so that the electrons in the center portion of the beam are largely wasted and only contribute to the production of the harmful space charge effects. For these reasons, considerable attention has been directed to producing hollow electron beams which possess the advantages of requiring lower operating voltages for a given power output and high beam perveance, and hence wider bandwidth and improved efficiencies of operation.

Because of the electrical current limitations of presently available cathodes, electron beams having high current density must have high convergence ratios, wherein convergence ratio is understood to mean the ratio of the cathode emitting surface area to the focused electron beam area. In general, it may be said that with given limitations on the current emission of the cathode and on the physical size of the interaction circuits, the limit on the power output of an electron beam tube is proportional to the ratio

$$\frac{(\text{convergence ratio})^{5/3}}{(\text{perveance})^{2/3}}$$

High perveance beams are desired for high power tubes, but unless the convergence ratio can be increased accordingly, no actual increase in power output is achieved.

One type of hollow beam gun that has been the subject of considerable interest is the so-called magnetron-injection gun that is disclosed in U.S. Patent 2,632,130, issued March 17, 1953 to J. F. Hull, and which is the subject of investigation in an article entitled "The Design and Performance of a Magnetron-Injection Gun," by Kino and Taylor, appearing on pages 1–11 of the January 1962 issue of IRE Transactions on Electron Devices. The authors Kino and Taylor describe a hollow beam gun comprised of an emitting cathode having the shape of a truncated right circular cone wherein the right circular cone has a half-angle of approximately 4°. Associated with this cathode is an anode which produces an electrostatic field having an axial component which tends to draw out in an axial direction the electrons which are orbiting about the cathode due to the presence of an axially-directed magnetic focusing field. While the magnetron-injection gun of the type disclosed in the above-cited reference has found use in lower power tubes in the lower microwave frequency ranges, attempts to adapt them for use in high power tubes and in the high frequency ranges have been less successful because the convergence ratios obtainable are limited, the beams are noisy, and the electron emission is intolerably non-uniform over the emissive surface of the cathode.

The limitations on the convergence ratio of the known magnetron-injection gun arises from the fact that the cathode used in these guns is in the form of a truncated right circular cone, and with such a cathode the convergence ratio must be lower than the value

$$\frac{1}{\sin \phi}$$

where ϕ is the half-angle of the truncated cone. This above relationship indicates that the half-angle of the cathode must be small in order to achieve higher convergence ratios. Limiting the half-angle of the conical cathode places a limitation on the magnitude of the axial component of the electric field at the emitting surface, and this has the effect of permitting the orbiting electrons to remain for a longer time in the cathode region, thus increasing the possibilities for the electron collisions and interactions that contribute to the noise on the beam. Patentee Hull has observed that the diameter of the base of the truncated conical cathode must not exceed the diameter of the aperture of the anode, the reason being that should this occur the electrons would strike the anode and the noise on the beam would increase. This again places a limitation on the convergence ratio that may be obtained with the magnetron-injection gun.

I have discovered that I can avoid the above-mentioned limitations by employing a concept based upon the use of a specially shaped magnetic focusing field, this shaped field being characterized by having magnetic flux lines that are substantially straight, parallel, and closely grouped in the central region of the field, but which diverge radially in a flare in the end region of the field and again become more closely grouped at their outer radii. The cathode is placed in this end region with the electron emissive surface conforming to, or slightly inclined backwardly with respect to the flaring magnetic flux lines. With this arrangement, the convergence ratio no longer is limited to the value

$$\frac{1}{\sin \phi}$$

and the emitting surface may have a considerable radial extent along the flaring flux line, thereby increasing the emissive surface area, and thus the convergence ratio and also producing a larger axial component in the anode-cathode electric field that tends to draw the orbiting electrons out of the cathode region, thereby to minimize the noise on the beam and promote uniform emission from the electron emissive surface.

The high convergence ratio comes about from the fact that electrons tend to follow the magnetic lines of force from the cathode to the high voltage beam region. With this greatly divergent magnetic field shape, the magnetic field helps to "compress" the beam that originated at the emissive surface having large radii throughout its length to a much smaller radius at the high voltage focused beam region.

It therefore is an object of this invention to provide an electron beam gun that produces a hollow electron beam having a high convergence ratio and a high perveance.

Another object of this invention is to provide an electron beam gun that produces a hollow beam having high perveance and high convergence ratio, and is characterized by substantially uniform emission from the cathode surface.

A further object of this invention is to provide a relatively stable and noise free hollow electron beam having high convergence ratio and high perveance.

A further object of this invention is to provide a hollow electron beam gun of the magnetron-injection type having a relatively large electron emissive surface.

Another object of this invention is to provide an electron beam gun that utilizes a shaped magnetic field to compress the electrons emitted from a cathode surface of large radius to a focused hollow beam of much smaller radius.

Still another object of this invention is to produce a hollow electron beam by means of a cathode having an electron emissive surface that is immersed in and proportioned in shape with respect to a shaped magnetic focusing field.

The present invention will be described by referring to the accompanying drawings wherein:

FIG. 1 is a perspective view, partially broken away, showing the cathode, anode, and focusing electrodes of the hollow beam gun of the present invention;

FIG. 2 is a somewhat schematic sectional view of electron gun of FIG. 1 showing the positions and shapes of the various components relative to the contour of the flux lines of the magnetic focusing field;

FIG. 3 is a sectional view similar to FIG. 2 and further showing, in a representative way, the formation of the hollow electron beam from the emitting surface of a cathode of this invention;

FIGS. 4, 5 and 6 are graphs used in explaining the design and operation of the hollow electron beam gun of this invention;

FIG. 7 is a simplified sectional illustration of an alternative embodiment of a hollow electron beam gun constructed in accordance with the teachings of the present invention;

FIG. 8 is a graph used in explaining the design and operation of the electron beam gun illustrated in FIG. 7.

FIGS. 9 and 10 are illustrations of alternative embodiments of the present invention; and,

FIGS. 11 and 12 are diagrams used in explaining the forces due to the magnetic field that act on electrons with different magnetic field patterns.

Referring now in detail to the drawing, a hollow electron beam gun constructed in accordance with the teachings of this invention is illustrated in FIGS. 1 and 2 and is comprised of focusing coil **11** and bucking coil **12** having like poles adjacent each other to produce a magnetic field having the pattern illustrated by the dashed lines **14** that represent the magnetic flux lines. As illustrated, flux lines **14** extend parallel and axially throughout the interaction region of the tube and diverge outwardly in a nonlinear flare in the end region of the field. As used in this description, nonlinear is intended to mean that a straight line relationship does not exist throughout the flared region. Coils **11** and **12** are normally disposed exteriorly of the tube envelope while of course the cathode, anode, focusing electrodes and the like are within the tube envelope.

Other arrangements may be employed for producing a magnetic field pattern of the desired shape. For example, one or more permanent magnets may be used, or combinations of permanent magnets and solenoids may be used. All these arrangements may include magnet pole pieces, if desired.

Cathode **17**, which is in the form of a figure of revolution, is positioned in the end region of the magnetic focusing field where the flux lines **14** diverge outwardly. The electron emissive surface **18** of the cathode **17** is disposed along the nonlinearly contoured sides of the cathode, and this surface is shaped to conform to the curvature of a magnetic flux line, or flux tube, upon which it lies. An annular anode electrode **20** is disposed coaxially in spaced-apart relationship about the electron emissive surface **18** and extends axially beyond the smaller end of cathode **17**, thus providing an electric field having a large axially-directed component to draw the spiraling electrons in an axial direction from emissive surface **18**. As may be seen, the electric field between the anode **20** and the back portion of cathode **17** that is of the largest diameter will be substantially wholly axially, thus drawing out the electrons from this back portion so as to decrease the possibility of electron interaction in this region, thus reducing the noise on the beam and promoting good electron emission from the rear of the surface **18**.

Electrostatic focusing electrodes **23** and **24** are positioned respectively at the front and rear edges of electron emissive surface **18** to aid in focusing the hollow electron beam. A drift tube **25** together with the desired interaction circuit (not illustrated) extend to the right of the gun.

It will be seen that the outwardly diverging surface **18** of cathode **17** provides considerably more electron emissive surface area than is available on the truncated right circular cone shaped cathode of the known prior art. For comparison purposes, for a given increase in the length at the back end of a cathode, the emissive surface of the shaped field hollow beam gun of this invention will increase by a larger percentage than will the cathode of the known prior art having the shape of a truncated right circular cone. This results from the fact that the rear area of the cathode of this invention will increase more nearly as the increasing area of a circle, while the increasing area of the prior art surface will be in accordance with the equation for the curved surface of the truncated right circular cone.

The formation of the thin hollow beam from the emissive surface illustrated in FIGS. 1 and 2 is represented by the sketch of FIG. 3 wherein it is seen that electrons emitted from the front edge of emissive surface **18** find an equilibrium position at the inner edge of the focused beam and electrons emitted from the back edge of the emissive surface find an equilibrium position at the outer edge of the focused beam. Electrons emitted from the intermediate areas of the emissive surface **18** find equilibrium positions between the inner and outer edges of the focused beam. Thus, the "compression" of the electrons from the cathode surface of large radii into a smaller diameter hollow beam is clearly evident from FIG. 3, and results from the specially shaped magnetic field which has the converging flux lines that are more closely grouped at the front end of the gun.

In order to arrive at the design objectives for an electron gun constructed in accordance with the present invention, and in order to determine its limitations, the following theoretical background is presented. However, before getting into the details of the theory to be followed, it will be helpful to keep in mind that the general approach is to provide a shaped magnetic focusing field wherein the field diverges outwardly in a nonlinear flare, and then position in the diverging region of the field an electron emitting surface having a definite relationship to the contour of the magnetic flux lines of the shaped field. For this reason it is necessary that an initial step in the design procedure be that the shape and magnitude of the magnetic focusing field be determined as accurately as possible.

It is assumed that the magnetic focusing field is axially symmetrical about a longitudinal axis which constitutes the central axis of the electron beam tube in which the gun is to be used. Therefore, the flux lines that are illustrated by the dashed lines in the drawings are representative of axially symmetrical lines of flux of tube-like form. It is further assumed that the electrons in the hollow beam travel with a common axial velocity. Since the electrons in the beam repel each other, there is always present a spreading force due to space charge within the beam. In order to maintain the hollow shape of the beam, other forces must be employed to neutralize the effects of this space charge force. These other forces are the Lorentz force due to the electrons cutting the magnetic field lines, the centrifugal force due to the

orbiting motion of the electrons, and the electric field forces due to electric potentials of the anode and the focusing electrodes.

Referring to FIG. 3, consider an electron located at the axial position Z_2 at a radius r from the axis of the axially symmetrical magnetic field, whose magnitude B is a function of r and Z. This same electron originated on the cathode emissive surface at an axial position Z_1. At axial position Z_2, the circle of radius r_a encloses the same magnetic flux as was originally enclosed by the same electron at position Z_1 on the cathode surface. For a substantially uniform magnetic field, the product Br_a^2 represents the initial magnetic vector potential of the electron. It is known from Busch's theorem of conservation of magnetic momentum that the angular frequency of an electron is

$$\dot{\theta}=-\omega_L\left(1-\frac{r_a^2}{r^2}\right) \tag{1}$$

wherein

$$\omega_L=\frac{1}{2}\frac{e}{m}B$$

is the Larmor frequency, e/m being the charge to mass ratio of an electron. The positive sense of angular rotation is defined as the mechanical angular momentum in the same direction as the magnetic vector potential. A negative $\dot{\theta}$ will result in a radial Lorentz force which decelerates the electron moving away from the axis or accelerates it toward the axis. A consequence of using Busch's theorem is that the angular velocity of an electron in an axial symmetric magnetic field, once the conditions at the cathode are established and known, is a function of its position only. A more important consequence, so far as the design of the shaped-field hollow beam gun of this invention is concerned, is that it deals only with the relationships between the flux at the cathode and that in the focused hollow beam, without having to consider what happens to the electrons in between these places. This means that there is considerable flexibility in positioning the cathode, once the shape of the magnetic field is known.

As a consequence of Busch's theorem we may express the forces that are available in the focused hollow beam to neutralize the space charge force by the following expression, which dimensionally is in units of electric field,

$$F=\frac{r}{\eta}\dot{\theta}^2+Br\dot{\theta} \tag{2}$$

wherein $\eta=e/m$. The first term on the right side of Equation 2 is the centrifugal force and the second term is the Lorentz force. In this development, Lorentz force is defined as being equal to $[-e(v\times B)]$, where e and B are as previously defined and v is the velocity of the electron. This definition omits the electric field term E which sometimes is included. The sign of F is positive when the force is directed outwardly from the axis.

Because the space charge E_s varies in the radial direction, i.e., rE_s is a variable, the product of radius and the constant electric field rE_L, provided by external electrodes cannot neutralize the space charge force. It is for this reason that the most important objective of magnetic focusing of a high density hollow beam is to derive a maximum variation of rF among electrons within the narrowest belt of radial space.

To examine this force rF, Equation 1 may be substituted into Equation 2 to give the following:

$$rF=-\frac{\omega_L^2r^2}{\eta}+\frac{\omega_L^2r_a^4}{\eta r^2} \tag{3}$$

The expressions for $\dot{\theta}$ and for rF are respectively plotted in FIGS. 4 and 5.

It will be further helpful to rewrite Equation 3 in the form

$$-\frac{\eta rF}{\omega_L^2r^2}=1-\left(\frac{r_a^2}{r^2}\right)^2 \tag{4}$$

and to rewrite Equation 1 in the form

$$\frac{r_a^2}{r^2}=\frac{\dot{\theta}}{\omega_L}+1 \tag{2}$$

and then substitute Equation 5 into Equation 4 to give the expression

$$\frac{\eta rF}{\omega_L^2r^2}=\frac{\dot{\theta}}{\omega_L}\left(2+\frac{\dot{\theta}}{\omega_L}\right) \tag{6}$$

which is plotted in FIG. 6. This graph shows the forces at a given radius r as a function of the angular velocity relative to the Larmor frequency

$$\left(\frac{\dot{\theta}}{\omega_L}\right)$$

and also shows the maximum negative force available when the angular velocity equals the Larmor frequency, i.e.,

$$\dot{\theta}=-\omega_L=\eta\frac{B}{2}$$

To compare the focusing of the hollow beam with that of the well-known Brillouin focusing technique for a solid beam, reference may be made to an article by applicant entitled, "Electron Beams in Axially Symmetrical Electric and Magnetic Fields," appearing on pages 135–147 of the February 1950 issue of Proceedings of the I.R.E. In this article Applicant teaches that the minimum magnetic field strength required for Brillouin focusing of a solid beam is at the point A in FIG. 6, and the magnitude of this field, is given by the expression

$$B_{min}=\frac{\sqrt{KV}}{1.203r} \tag{7}$$

wherein K is the microperveance of the beam, V is the beam operating voltage, and r is the beam radius. If an electron is emitted from a cathode which encloses magnetic flux, the operating range on the curve of FIG. 6 will shift to the right of point A, that is, to the ABOC portion of the curve, if the flux through the cathode is in the same direction as the main magnetic focusing field. The operating range will shift to the left of point A, the AEL portion of the curve, if the direction of the magnetic flux enclosed by the cathode opposes the direction of the main magnetic focusing field. This latter portion of the curve AEL is of little interest, however, because of the difficulty of producing a beam that will work well in the transition region from one direction of magnetic field to the other. Also, because there is mirror symmetry of the curve about the point A, forces corresponding to points on the portion of the curve ABOC involve less angular velocity than points on the portion of the curve AEL that represent the same amount of force. Therefore, by using the portion of the curve ABOC, more axially-directed kinetic energy is available in the beam for interaction with electromagnetic waves.

The portion of the curve ABOC of FIG. 6 is indicated by similar letter designations on the curve of FIG. 5. In FIGS. 4 and 5, the conditions of zero angular velocity and zero force correspond to the points $r=r_a$. As may be seen of FIG. 4, the Larmor frequency $-\omega_L$ that is designated by the point A in FIG. 6 is reached only when the operational radius r is large in comparison with r_a. The limit corresponding to point A in FIG. 6 is indicated in FIG. 5 by the dashed curve $-\omega_L^2r^2/\eta$. For the focusing of the hollow electron beam in accordance with this invention, wherein r_a has a finite value, references to FIGS. 4 and 5 will show that the operational range B of FIG. 6 has an angular rotational frequency less than the Larmor frequency, and the negative force available for focusing the beam is less than the maximum obtain-

able force for a given magnetic field strength. When r is less than r_a the curves of FIGS. 5 and 6 show that the force F becomes positive. As seen in FIG. 4, when r is very much smaller than r_a, θ is very large, the Equation 2 indicates that when this condition exists the centrifugal force is predominant. Otherwise, the centrifugal force is relatively small compared to the Lorentz force.

For most practical uses of a hollow electron beam, such as in traveling wave tubes and klystron tubes, the beam will be surrounded by a metallic circuit and all the electric field lines emanating from the space charge will terminate on this metallic conductor. With this condition present, there will be no electric force on the inside edge of the beam so that the balancing force there also must be zero. For this reason, the operational points on FIGS. 4 and 5 for the electrons on the inner edge of the hollow beam are on the zero θ and rF axes where $r=r_a$. The operational point for electrons on the outer edge of the hollow is in the region of FIG. 5 designated B, at a radius $r=r_0$ and the electrons between the edges fall on the portion of the solid curve designated OB.

It can be shown that to have a complete equilibrium beam with forces balanced at all points within the beam, the space charge density distribution should follow the form

$$\rho_o=\frac{\rho_{oa}}{2}\left(1+\frac{r^4_a}{r^4}\right) \tag{8}$$

wherein ρ_{0a} is space charge density at the inner edge of the beam. The electrostatic field E_s that results from the space charge density distribution expressed in Equation 8 has the following form:

$$\eta r E_s=\frac{\omega^2_{ea}r^2}{4}\left[1-\frac{r^4_a}{r^4}\right] \tag{9}$$

where $\omega^2_{ea}=\eta\rho_{0a}/\epsilon_0$ is the square of the plasma frequency at radius r_a, ϵ_0 being the permittivity of a vacuum.

Comparing Equations 4 and 9, it will be seen that the space charge force is balanced by the sum of the Lorentz force and the centrifugal force when

$$\omega_L{}^2=\frac{\omega^2_{ea}}{4} \tag{10}$$

To compare the magnetic field required to focus a hollow beam with that required to focus a solid beam having the same θ, the plasma frequency ω_e and the Larmor frequency for the solid beam case are related by the expression

$$\omega_{Lm}{}^2=\frac{\omega_{em}{}^2}{2} \tag{11}$$

The subscript m indicates the minimum magnetic field case. In order to keep the same total perveance and the same outer radius for the two cases, we must have

$$\omega_{em}{}^2=\frac{\omega_{ea}{}^2}{2}\left(1-\frac{r_a{}^4}{r_o{}^4}\right) \tag{12}$$

From the above, the ratio of the Larmor frequency to the minimum Larmor frequency required, is

$$\left(\frac{\omega_L}{\omega_{Lm}}\right)^2=\frac{1}{2}\left(\frac{\omega_{ea}}{\omega_{em}}\right)^2=\frac{r_0{}^4}{r_0{}^4-r_a{}^4}$$

or

$$\frac{B}{B_{min}}=\left(1-\frac{r_a{}^4}{r_0{}^4}\right)^{-1/2} \tag{13}$$

In terms of Equation 7, the magnetic field required for the hollow beam case becomes

$$B=\frac{\sqrt{KV}}{1.203r_0}\left(1-\frac{r_a{}^4}{r_0{}^4}\right)^{-1/2} \tag{14}$$

The above comparison with a solid electron beam, and the resulting Equation 14 are valid because the outer electrons in both the solid and hollow beams will have the same space charge forces and the focusing force F on the outer electrons of both beams will be the same because θ was assumed to be the same in both cases. Equation 14 therefore indicates that with an arrangement as illustrated in FIG. 2 wherein the electron emissive surface is shaped and positioned to conform to an outwardly flaring magnetic flux line, a hollow electron beam having an inner radius of r_a and an outer radius of r_0 may be produced with a magnetic focusing field having a magnitude of B gauss.

Again, the advantages arising from the use of the cathode constructed in accordance with this invention are that the cathode emitting area may be made much larger for a given linear length than with the truncated right circular cone cathode. Further, because of the outward flares of the emitting surface and the anode, the electric field normal to the emissive surface has a very large component in the axial direction, thus drawing the electrons from the cathode surface and thereby reducing noise and producing more uniform emission from the emitting surface. The net accomplishment is the creation of a higher perveance beam having lower noise, and without the necessity for any sacrifice in the convergence ratio or increase in the strength of the magnetic focusing field.

For the purpose of the above investigation it was assumed that electrons from the front and back edges of emissive surface **18** reached equilibrium positions, respectively, at the inner and outer edges of the focused beam. It should be understood that it is a theoretically assumed condition which may be achieved in practice, although this does not invalidate the above development.

An alternative embodiment of the present invention is illustrated in simplified form in FIG. 7 and enables one to obtain an even thinner hollow beam with a given focusing magnetic field strength than with the arrangement illustrated in FIGS. 1 and 2. In the embodiment of FIG. 7, the back end of the cathode is tilted backwardly from the magnetic flux line on which the front edge of the cathode is coincident so that the electrons emitted from the back edge of the cathode are at a lower magnetic vector potential than those emitted from the front edge. The focusing forces on the electrons emitted from the front and back edges of the emitting surface **38** of FIG. 7 are illustrated in the diagram of FIG. 8 in which the curve **40** illustrates the magnitude of the forces acting on electrons emitted with the same magnetic vector potential $Br_a{}^2$ as an electron emitted from the front edge of emitting surface **38**. Curve **41** represents the magnitude of the forces acting on electrons emitted with the same magnetic vector potential $B'r'_0{}^2$ as an electron emitted from the back edge of emitting surface **38**. The solid line **44** represents the forces acting on the electrons emitted from the region between the front and back edges of the emitting surface **38** of FIG. 7. It may be seen that the thickness (r_0'—r_a) of the focused beam is less in this embodiment than it would be (r_0—r_a), in the embodiment of FIGS. 1 and 2. In a practical situation this means that for a given beam thickness the magnetic field may be less than indicated by Equation 13, or for the same magnetic field strength, the convergence ratio can be made larger. Conversely, it is true that a thicker beam will result, and hence a lower convergence ratio, if the electron emissive surface is tilted the other way so that the back edge of the surface is at a higher magnetic vector potential than the front edge. This has been experienced in the use of the prior art magnetron-injection gun that employs a substantially uniform axial magnetic field.

It will be noticed that by tilting the emissive surface toward the rear the cathode-anode electrostatic field at the emissive surface has less of an axially directed component. However, by assuring that the magnetic field flux lines extend outwardly as radially as possible, the cathode may be tilted backwardly with respect to a flux line and yet permit the cathode-anode electrostatic field to have an appreciable axial component.

Maximum advantage may be taken of the axial electric field between the anode and cathode by an embodi-

ment of the invention illustrated in simplified form in FIG. 9, wherein the electron emissive surface **68** of the cathode **70** is positioned and shaped to conform to the extreme outwardly extending portion of the flaring tube-like lines of flux. Front and back focusing electrodes **71** and **72** serve the same function as that previously described for the corresponding electrodes in the electron gun illustrated in FIGS. 1 and 2. In this embodiment of the invention, the projection of the emissive surface **68** onto a plane normal to the center axis of the tube is very large while the projection of the surface **68** onto a plane parallel to the center axis is quite small whereby the electric field gradient between anode **74** and emissive surface **68** is very nearly axial so that electrons are emitted from surface **68** with a very large initial axial velocity, thereby promoting uniform emission and low noise. Furthermore, the outer radius at the back end of emissive surface **68** is quite large so that the convergence ratio achieved with this embodiment of the invention will be considerably larger than with the previously described embodiments. The principles of operation of the electron gun of FIG. 9 is the same as for the previously described embodiments of the invention.

Another shaped-field hollow beam electron gun constructed in accordance with the teachings of this invention is illustrated in FIG. 10 wherein the focusing magnetic field is shaped to present parallel flux lines in the central region of the field, but in the end region of the field the flux lines flare outwardly and reverse their slopes at the far radial extent of the field. In this instance, electron emissive surface **80** is shaped and positioned to conform to the portions of flux lines **82** and **83** having reverse slopes so that electrons emitted from surface **80** will initially be directed inwardly toward the axis of the gun. Anode electrode **85** is positioned coaxially about the axis of the gun in the forward region thereof so as to establish the proper electric field to draw the orbiting electrons into the focused beam. Focusing electrode **87** is positioned coaxially about the front edge of emissive surface **80** and focusing electrode **88** is positioned about the central axis of the gun to aid in focusing the hollow beam. In this embodiment of the invention the electrons emitted from the back edge of electron emissive surface **80** theoretically will find equilibrium positions at the inner edge of the focusing hollow beam while the electrons emitted from the front edge of electron emissive surface **80** will find their equilibrium positions at the outer edge of the hollow beam.

As may be seen from the various embodiments of this invention previously described, there is considerable flexibility in designing an electron hollow beam gun in accordance with the teachings of this invention. In all of these embodiments large emissive surface areas, and hence large convergence ratios, are readily obtained for high perveance beams.

One further and important consideration must be given to the forces acting on the electrons leaving the emissive surface of an electron gun constructed in accordance with this invention, and this consideration further emphasizes the importance of producing the specially shaped magnetic field. This consideration involves the direction of the axial force on the electrons due to the magnetic field. Obviously it is desirable for optimum efficiency of operation that the axial forces due to the electric and magnetic fields act in the same direction so as to direct the electrons toward the front end of the gun. This condition, however, does not necessarily follow for all geometrical relationships between the shape and location of the electron emissive surface and the magnetic field flux lines. FIG. 11 is a diagram used to illustrate the situation in which the axial force on an electron *e* is in the backward direction, opposite the direction of the force due to the electric field established between the anode and cathode. In this discussion, forward and backward are in reference to a line normal to the electron emissive surface **91**. For simplicity, only one half of the cathode is illustrated in FIG. 11, it being understood that the cathode is a figure of revolution that is symmetrical about the center axis, as illustrated in FIG. 1.

In FIG. 11 the electron emissive surface **91** is shaped to conform to the outwardly flaring flux line **93**, and the flux line **94** which is radially beyond emissive surface **91** is parallel to the flux line **93** in the region of the emissive surface **91**. The centrifugal force acting on electron *e* is directed radially outwardly, and the Lorentz force acting on electron *e* is normal to flux line **94** and falls on top of the normal to the emitting surface **91** because the flux lines **93** and **94** are assumed to be parallel. It may be seen that the resultant of the centrifugal force and the Lorentz force falls in back of the normal to the emitting surface and therefore has a backward component force that would tend to direct electron *e* toward the rear of electron emissive surface **91**.

Satisfactory operation of an electron gun with the arrangement illustrated in FIG. 11, wherein the emissive surface is parallel to the flux line **94** still is possible, the only result being that this type of gun is not as efficient as possible because the cathode to anode electric field now must be large enough to overcome the backward component of the resultant magnetic force and to draw the electrons out of the front end of the gun. All of the theoretical considerations that went into derivations of Equation 13 still are valid since they are concerned only with the radial forces acting on electron *e*.

FIG. 12 illustrates the situation wherein the axial force on an electron *e* due to the summation of the centrifugal force and the Lorentz force produces a forwardly directed force component to urge the electron out of the front end of the gun, thus aiding the force due to the cathode-anode electric field. In the arrangement illustrated in FIG. 12, electron emissive surface **91** again is conformal to the flux line **93**, but the flux line **95** which electron *e* is cutting is not parallel to the flux line **93** but is tilted backwardly so as to have less slope with respect to the axis in the central region of the emissive surface **91**. The centrifugal force still is directed radially outward and the Lorentz force, which is normal to flux line **95**, now is in front of the line normal to emissive surface **91**. The resultant of the centrifugal force and the Lorentz force also is on the forward side of the normal to emissive surface **91** and has a forwardly directed component of force which urges the electron *e* out of the front end of the gun, thus aiding the force due to the cathode-anode electric field. This relationship between the slopes of the flux lines is more desirable than that illustrated in FIG. 11 because the smaller anode voltage is required to draw the electrons from the gun.

Therefore, in summary, to produce a magnetic field in accordance with the teachings of this invention, it is necessary to keep in mind that the radially more distant flux line **95** should have less slope than the flux line coincident with the emissive surface in the region of the emissive surface, or at least in the central region thereof, in order that the Lorentz force vector be in front of the normal line to the emissive surface. Further, to assure good "compression," or convergence ratio the flux lines should be more closely grouped in the region at the front of the gun and at the radially most distant regions of the field.

The magnetic field pattern having flux lines with the relationship illustrated in FIG. 12 is relatively easy to obtain with conventional solenoids, magnets, and pole pieces that are commonly used in the construction of electron tubes.

In the design of a hollow beam gun in accordance with the present invention, the first step is to produce the magnetic focusing field that has the shape just described and illustrated in the accompanying drawings. One way of producing such a field is by means of oppositely polarized solenoids or permanent magnets placed end to end, with

or without a pole piece therebetween. By using solenoids, the flare of the magnetic focusing field can be controlled over a large range. The shape of the magnetic field is plotted either by using iron filings or a magnetic field probe.

The outer radius of the beam must conform to the size of the interaction structure with which it is to be used, and since the inner radius of the beam generally will be along the same flux line as the front edge of the emissive surface, the desired flux line that the emissive surface is to follow may be chosen in order to insure a given beam thickness.

Next the shape and position of the anode **20**, FIG. 2, is determined in order to provide an appreciable axial electric field, and to avoid intercepting the electrons since this reduces the beam current and increases the noise on the beam. As a preliminary guide in arriving at the anode shape, the so-called Hull cut-off lines may be used as a starting design. These lines are determined by the following equation

$$V=\frac{B^2R_a^2}{45.48}\left(1-\frac{R_c^2}{R_a^2}\right)^2 \qquad (15)$$

where V is the desired anode voltage, B is the measured magnetic field in gauss, R_c and R_a are the radii of the cathode and anode, respectively, in centimeters. By employing known methods, the final design and shape of the anode surface is determined.

After the shapes and positions of the electron emissive surface and the anode have been determined, the shapes, positions, and potentials of the front and back focusing electrodes **23** and **24** of FIG. 2 are determined. These electrodes provide means for exercising a final control over electron trajectories to further enable the designer to achieve the desired beam characteristics. The shapes and positions of focusing electrodes **23** and **24** may be arrived at with the aid of an electrolytic tank and an analog computer, the procedure followed being known to those skilled in the art.

An electron gun constructed in accordance with the teaching of this invention had the following physical and electrical characteristics:

Emissive surface area, sq. cm.	24
Front radius of emissive surface, inch	.419
Back radius of emissive surface, inch	.905
Magnetic field strength, gauss	580
Anode-cathode voltage, volts	380
Beam current, milliamps	227
Microperveance	30
Convergence ratio	50
Anode intercept, percent	1
Relative beam thickness, percent	9

where relative beam thickness is defined as

$$\frac{\text{(beam outer radius)}-\text{(beam inner radius)}}{\text{beam outer radius}}$$

While the invention has been described in its preferred embodiments, it is to be understood that the words which have been used are words of description rather than limitation and that changes within the purview of the appended claims may be made without departing from the true scope and spirit of the invention in its broader aspects.

What is claimed is:

1. Electron gun means for producing a focused hollow electron beam directed along a longitudinal axis, said gun comprising,

means for producing a magnetic field having lines of flux that extend radially outwardly from said axis at the back region of said gun and converge with a nonlinear taper toward said axis at the forward region of said gun,

an electron emitting means positioned in the radially outwardly extending portion of said magnetic field and having an electron emissive surface arranged in shape and positioned so that said surface generally follows the contour of those flux lines lying immediately adjacent said surface and between the ends thereof, and

means for exerting an axially directed force on electrons emitted from said emitting means to draw said electrons toward the front end of said gun.

2. The combination claimed in claim **1** wherein said electron emitting means is a surface of revolution that extends at least in part in an axial direction along said gun.

3. The combination claimed in claim **2** wherein said electron emitting surface is substantially conformal to nonlinear lines of flux.

4. An electron beam gun adapted to produce an axially directed hollow electron beam, said gun comprising,

electron emitting means having an axially extending electron emissive surface in the shape of a figure of revolution having a first diameter at the front end thereof nearest the front of said gun and extending outwardly in a nonlinear flare to a second larger diameter at its rear,

means for producing a focusing magnetic field having flux lines that diverge outwardly in a nonlinear flare in the direction toward the rear of said gun,

said electron emitting means being immersed in said magnetic field in a zone thereof wherein the lines of flux diverge outwardly in a nonlinear flare from the front end toward the rear of said electron emissive surface,

means for exerting an axially directed force on electrons emitted from said surface to draw said electrons from said surface toward said one end.

5. An electron beam gun adapted to produce an axially directed hollow electron beam, said gun comprising,

electron emitting means having an axially extending electron emissive surface in the shape of a figure of revolution having a first diameter at the front end thereof nearest the front of said gun and extending radially outwardly in a nonlinear flare to a second large diameter at its rear,

means for producing a focusing magnetic field having flux lines that diverge outwardly in a nonlinear flare in the direction toward the rear of said gun,

said electron emitting means being immersed in said magnetic field in a zone thereof wherein the lines of flux diverge outwardly in a nonlinear flare from the front end toward the rear of said electron emissive surface,

an anode electrode disposed in coaxial and spaced apart relationship to said emissive surface, the surface of said anode flaring outwardly in the direction toward the rear of said gun thereby to produce an axially directed component of electric field between said emissive surface and said anode.

6. Apparatus for producing a hollow electron beam directed along a longitudinal axis, said apparatus comprising,

means for producing an electron beam magnetic focusing field having flux lines that extend radially outwardly at a first region and converge with a nonlinear taper toward said axis at a second region,

an electron emitting surface disposed about said axis in the region of said magnetic field and having a shape substantially conforming to and coincident with the lines of flux of said magnetic field, and

means for exerting an axially directed force on electrons emitted from said surface to draw said electrons from said surface toward said second region.

7. Apparatus for producing a hollow electron beam directed along a longitudinal axis, said apparatus comprising,

means for producing a magnetic field that is symmetrical about said axis and has a pattern of flux lines

that extend radially outwardly at a first region and converge with a non-linear taper toward said axis at a second region,

an electron emitting surface disposed symmetrically about said axis in the region of said magnetic field,

said surface extending radially outwardly in said first region of the field and converging with a non-linear taper toward said axis at the second region of said field,

said emitting surface being non-conformal to the magnetic field flux pattern with its end at said first region at a lower magnetic vector potential than its end adjacent said second region.

8. The combination claimed in claim **7** and further including,

an anode electrode disposed symmetrically about said axis in spaced apart relationship from said emissive surface,

said anode extending axially beyond said surface in said second region of the magnetic field and diverging outwardly with a nonlinear flare toward said first region.

9. An electron gun for producing a hollow electron beam directed along a longitudinal axis, said apparatus comprising,

means for providing an electron beam magnetic focusing field that is characterized by having a pattern of flux lines that are substantially axially directed in a first region of said field and are radially diverging with a nonlinear flare at a second region of said field,

electron emitting means comprising an electron emitting surface symmetrically disposed about said axis in said second region of the focusing field where the flux lines diverge radially and having its surface diverging in the direction in which said field diverges,

said electron emitting means being located so that the lines of flux lying between the ends thereof and adjacent the said surface thereof and which are coincident with the surface of said emitting means at the front end thereof will have a divergence not less than the divergence of said surface.

10. Electron gun means for producing a focused hollow electron beam directed along a longitudinal axis, said gun comprising,

means for providing an electron beam magnetic focusing field having a pattern of flux lines that converge toward said axis at a first region and diverge radially in a nonlinear flare at a second region,

the flare of said flux lines in said second region being characterized by having slopes of one sense along their respective portions nearest said axis and having slopes of an opposite sense along their respective portions most distant from said axis,

an electron emitting surface disposed about said axis in the second region of said magnetic field where the flux lines have slopes of said opposite sense,

said surface facing inwardly to emit electrons toward said axis, and

means for exerting a force on said electrons to direct them toward said first region.

11. An electron gun for producing a hollow electron beam directed along a longitudinal axis, said apparatus comprising,

means for providing an electron beam magnetic focusing field that is characterized by having a pattern of flux lines that are substantially parallel and axially directed in the central region of said field and radially diverging with a nonlinear flare at an end region of said field,

an electron emitting surface symmetrically disposed about said axis in said end region of the focusing field where the flux lines diverge radially,

said emitting surface being conformal to the contour of the magnetic field flux pattern present at its location.

12. The combination claimed in claim **11** and further including,

an anode electrode disposed coaxially in spaced apart relationship about said emissive surface and extending beyond the end of said emissive surface in the direction toward the central region of said field and diverging radially in a nonlinear flare at its opposite end, thereby to produce an axial component of electric field between said anode and said emissive surface.

13. The combination claimed in claim **12** and further including,

first and second focusing electrodes respectively positioned adjacent the two ends of said emissive surface,

said electrodes being positioned and electrically biased to further control the shape of said hollow electron beam.

14. Apparatus for producing a hollow electron beam directed along a longitudinal axis, said apparatus comprising,

means for producing an electron beam magnetic focusing field having flux lines that extend radially outwardly at a first region along said axis and converge with a nonlinear taper toward said axis at a second region axially displaced from said first region,

an electron emitting surface disposed about said axis in the region of said magnetic field and having a shape substantially conforming to and coincident with the said flux lines of said magnetic field.

15. The combination claimed in claim **14** wherein the flux line to which said electron emitting surface conforms has a greater slope in the region of said surface than the flux lines that are radially more distant from said surface.

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