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APPARATUS FOR GENERATING HOLLOW ELECTRON BEAMS

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Fig. 1

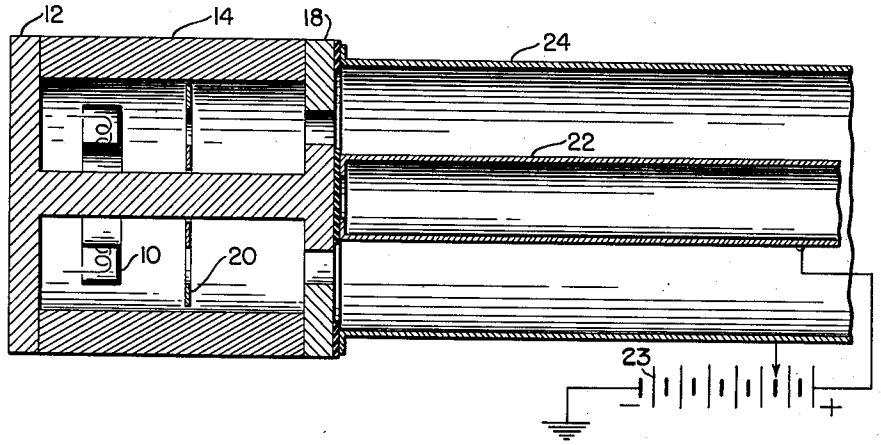


Fig. 2

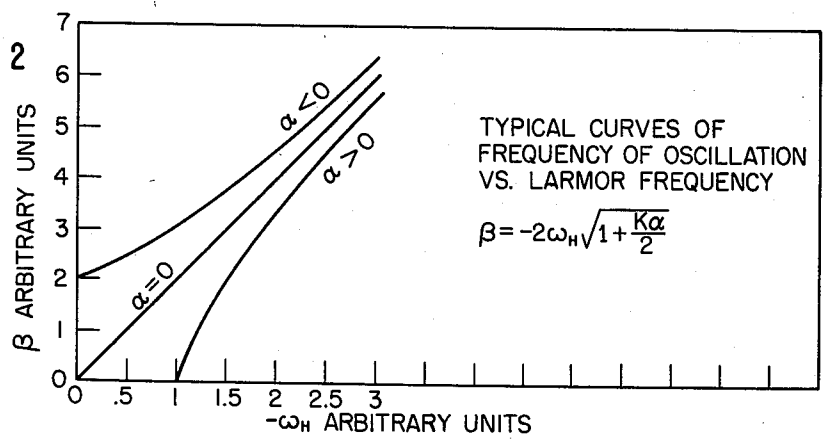
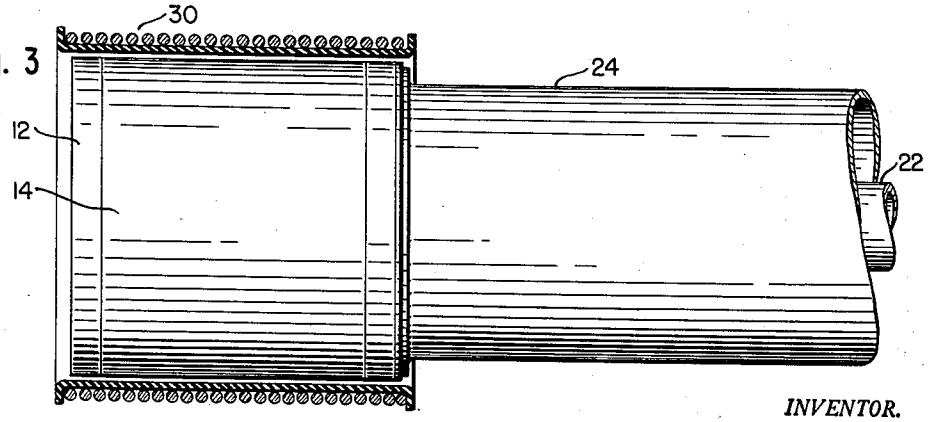


Fig. 3



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APPARATUS FOR GENERATING HOLLOW ELECTRON BEAMS

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This invention concerns the production and focusing of axially symmetric hollow electron beams and more specifically the production and maintenance of such beams without the necessity for a magnetic field along the entire axis of the beam.

Many microwave vacuum tubes make use of an electron beam. In the past it has been common practice to use a strong magnetic field along the axis of such a beam in order to convert any undesirable radial motion into angular motion and thus keep the beam well focused. Many analyses, being founded on the idea of using a solid beam, assumed infinitely intense magnetic fields and much power has been wasted in producing fields which approximate this assumption. The power requirements for producing such a magnetic field along the entire axis of the beam have been on important part of the total requirements for these tubes.

In many cases, however, there is no inherent necessity to use a solid beam. In certain applications, even without considering questions of economy, a hollow beam may be more desirable. The apparatus necessarily involved in producing a hollow beam consists of an electron gun which is capable of producing the electron beam required, and an evacuated drift tube in which the beam travels, this latter being simply a piece of hollow metal tubing. Existing systems also commonly use a solenoid somewhat longer than the tube itself in order to produce a uniform longitudinal magnetic field in the tube. Excluding factors which may be introduced by the electron gun itself, an electron moving in the drift tube part of such apparatus would be influenced by a variety of forces. The gun produces axial velocity which the electron will maintain. At the same time, the density of the beams which are involved here is such that the electrons tend to react against each other. The net effect is a strong tendency for the beam to expand unless restrained by some other force, this tendency being known as the space charge effect. If the beam does start to expand, however, the electrons must cross the longitudinal lines of flux produced by the axial solenoid and in so doing the expansion is converted into rotation. One further influence which may be applied to an electron in a hollow beam would be the force of an electric potential which could be applied by placing another conductor inside the outer drift tube but inside the hollow beam and then keeping the two drift tubes at different voltages. The potential gradient thus set up would tend to force any given electron toward the more positive electrode.

It is the object of this invention to provide a simpler and more efficient and economical method of producing and maintaining a hollow electron beam. More specifically it is the object of this invention to enable the maintenance and focusing of such a beam without the use of a magnetic field along the axis of the beam.

To achieve these objects this invention contemplates the use of an electron gun, a casing around the gun in which a magnetic flux is created having an annular opening through which the beam passes, said opening being traversed by flux having radial components, and a coaxial drift tube in registration with the beam on the two electrodes of which there is a potential difference. It will be noted that this apparatus requires the use of a magnetic field in the beam forming region only, thus making a simpler apparatus and eliminating the need for the main coils and power supplies now used. A further advantage is the fact that mechanical alignment between the magnetic field and the drift tube is no longer a problem, and the tube may be relatively easily connected to radio frequency apparatus.

In the drawings illustrating the invention, Fig. 1 shows a longitudinal cross section schematically representing one form of the invention; Fig. 2 is a plot of angular frequency vs. a quantity proportional to the axial flux; Fig. 3 shows another form of the invention in which a solenoid is added to counteract stray flux permeating into the area of an incompletely shielded cathode.

Fig. 1 schematically illustrates the above-mentioned parts as follows: An electron gun consisting of an annular cathode **10** and an annular anode **20** are contained in the metal case (e. g. soft iron) **12**. A flux producing device **14** (in this example a cylindrical permanent magnet) sets up in the shield a flux which passes radially across the gap in the shield **18** through which the beam passes. The entire construction is similar to that of a dynamic loudspeaker magnetic circuit and the radial flux across the anode gap is the essential part of the system. It is at present deemed desirable that this magnetic air gap be placed well forward of the anode of the electron gun in order that the cathode region be as free as possible of any fringing magnetic flux. The inner and outer drift tube electrodes are denoted **22** and **24** respectively and are insulated from each other and from the case. The entire apparatus is, of course, evacuated in the standard manner. Since the figure is intended to be merely diagrammatic all leads are omitted.

In broad terms, the apparatus functions as follows. Electrons emitted by the cathode are accelerated by the anode and are formed by the configuration of the gun into a beam. In this case a hollow configuration such as that which may be produced by a Pierce type gun is preferred. The beam so produced is sufficiently dense so that the reaction of one electron against another (i. e. space charge effects) would by themselves result in the beam beginning to expand and diffuse were other forces not applied.

Traditionally, a magnetic field having strong axial components is used to change radial motion into angular motion and form, in most cases, a relatively solid beam. In the present invention, however, the entire beam crosses radial flux before entering an annular waveguide passage, and in so doing the entire beam acquires a rotational velocity component about its axis which varies with radius, after which it enters the drift tubes upon which a potential difference exists (imposed, for example, by the battery **23**) tending to force the electrons inward. Axial components of flux used in existing systems for focusing dense beams are unnecessary, focusing being instead accomplished by the carefully combined effect of radial flux in the beam focusing region and a potential difference on the coaxial drift tubes which form the waveguide passage.

Neglecting interaction between electrons other than that tending to produce expansion, each electron in such a system is acted on by three forces; namely, the space charge effect, the centrifugal force due to the rotation acquired from the magnetic field, and the force of the applied electric field. The first two tend to force expansion whereas the latter counteracts this tendency. However, the gradients are not the same for the different

forces applied, and in order to produce stability and hence a focusing effect the density of the beam must adjust itself in such a way that the gradient due to space charge effects just balances those from the other applied forces. The charge distribution which achieves this result is one in which the electrons are concentrated quite heavily on the inside of the beam. While in some cases this may be a severe limitation, it may also be an advantage. For example, it would be very efficient in a coaxial type of traveling wave tube if the inner electrode rather than the outer one were corrugated to slow the wave.

The feasibility of the above method of focusing may be explained by the necessity for the beam to conserve energy. The beam does not have enough energy to expand, and it cannot collapse because of the requirement for conservation of angular momentum. A mechanical analogy might be that of a ball spinning around the sides of a bowl in a gravitational field, for a similar balance of forces keeps the ball at some radius part way up the sides of the bowl. This description of the focusing effect neglects certain details such as possible ionization effects, interaction of electrons due to their trajectories crossing radially, and the like, since these factors need not be of critical importance.

Two fundamental laws, conservation of energy and conservation of angular momentum, determine the behavior of the electrons in the beam and therefore the beam itself. If we assume a cylindrical system of coordinates wherein z is the position along the longitudinal axis, r is the radius, and θ the angle involved, then

$$\dot{r}^2+r^2\dot{\theta}^2+\dot{z}^2=-2\frac{e}{m}\varphi$$

The dot notation indicates time derivatives, e is the charge on the electron (-16×10^{-20} coulomb); m is the electron mass (9.1×10^{-31} kg.). φ is the electric potential of the point as measured from the cathode. All electrodes and potentials are independent of θ and z, as is the magnetic field, for the analysis starts with the assumption of an axial magnetic field. The magnetic field due to the beam current is ignored and the electrons are assumed to have started with zero velocity (i. e. no velocity of emission) so that the velocity will depend on the anode's accelerating voltage V.

For analysis purposes the beam is assumed to consist of a series of cylindrical shells with no radial crossing, each shell enclosing the same charge. Each electron is in fact dependent on the course of every other electron; however, such a system would not be subject to analysis. In order to have such a system it is necessary to approximate the true system by assuming a radius at which equilibrium is possible.

Making the above assumption and using known mathematical procedures the following equation may be derived:

$$\dot{r}^2=-2\frac{e}{m}\alpha ln\frac{r}{r_0}-2\frac{e}{m}(\gamma-V)-\left(\frac{e/m}{2\pi r}\right)^2(\psi_c-\psi)^2$$

where α is a coefficient giving the magnitude and direction of the radial electric field, γ is the average potential at r_0, r_0 is the equilibrium radius at which thte electrons of a shell experience no radial force, V is the accelerating voltage,

$$\left(\dot{z}^2=-2\frac{e}{m}V\right)$$

and ψ denotes the flux (subscript c denotes cathode).

The equation for radial acceleration may then be found from the derivative of the above equation. Further calculation (including in approximating

$$2ln\frac{r}{r_0}$$

which equals

$$ln\frac{R}{R_0}\text{ by }\frac{R}{R_0}-1\Big)$$

results in the following equation for angular frequency of radial oscillation

$$\beta=-2\omega_H\sqrt{1+\frac{K\alpha}{2}}$$

where

$$\omega_H=\frac{e}{m}\frac{B}{2},\ B=\frac{\psi}{\pi r^2}\text{ and }K=\frac{e/m}{\omega_H^2r_0^2}$$

This equation is of considerable significance. In a stable beam β as defined above must be real. A plot of β as a function of $-\omega_H$ (which is proportional to flux density B) is shown in Fig. 2. This plot shows that when an electric potential tending to force the electrons inward is applied to the drift tube β remains real (and the beam stable) even though the magnetic field is reduced to zero.

Design equations resulting from such an analysis where the flux is equal to zero may be summarized as follows:

$$B_{eff}=\frac{\psi_c}{\pi r_a r_b}\qquad B_{eff^2}=\frac{6.9\times10^{-7}}{r_b^2-r_a^2}\frac{I}{\sqrt{V}}$$

$$\rho=\frac{e}{m}\frac{\epsilon}{2}\frac{\psi_c^2}{\pi^2r_0^2}$$

$$\varphi_1=V-\frac{e}{4m}\left(\frac{\psi_c}{\pi r_a}\right)^2\left(ln\frac{r_a}{r_1}+\frac{1}{2}\right)$$

$$\varphi_2-\varphi_1=\frac{e}{4m}\left(\frac{\psi_c}{\pi r_a}\right)^2\left[\left(ln\frac{r_a}{r_1}+\frac{1}{2}\right)+\frac{r_a^2}{r_b^2}\left(ln\frac{r_2}{r_b}-\frac{1}{2}\right)\right]$$

where I is the beam current, ρ is the linear charge density of the beam, φ_1 and φ_2 are the inner and outer electrode potentials, r_a and r_b are the inner and outer beam radii, and ϵ is the permittivity of free space ($\frac{1}{36\pi}\times10^{-9}$ farads/meter). The same equations for charge density, magnetic field strength, and difference between electrode voltages may be obtained by balancing radial electric, centrifugal, and magnetic forces; however, the actual voltage of the inner electrode (φ_1-V), is, of necessity, derived from the energy balance.

Typical design parameters derived from these calculations are as follows:

$\psi_c=5.47\times10^{-6}$ Weber
$\varphi_1=1885$ volts
$\varphi_2=1183$ volts

An experimental model showed maximum focusing at values which were in close agreement with the above calculations φ_1 being 1870 volts and φ_2 1175 volts.

The effectiveness of these parameters is based on the assumption that the cathode region is completely shielded from stray flux, and that all the flux passes through the annular gap in the shield. While placing the air gap sufficiently far forward of the anode should reduce fringing to negligible amounts, it may be useful under certain conditions to place a short solenoid over the entire gun structure to produce a field capable of compensating for and neutralizing any stray flux in the cathode region. Fig. 3 illustrates this procedure, the solenoid being designated 30.

It will be noted that the charge density of the beam varies as $1/r_0^4$. This means that if the currently preferred Pierce type gun is used, in which the cathode emits electrons in such a way as to produce a uniform beam, there is a shift of charge density toward the inside during the transient region. However, where the gun is shielded the transition region (flux gap) is likely to be short, and this phenomenon should not materially influence focusing.

As heretofore noted the foregoing analysis depends on certain assumptions, of which the only seriously questionable one is the assumption of no radial crossing. This means that the shells must have the same wavelength and phase and hence that β must be the same for

all shells and independent of r_0 or of R_0. If the density is non-uniform the frequency is not independent of r_0, and the assumption of no radial crossing is unjustified when oscillations take place. However, those conclusions are valid for equilibrium conditions, and have been verified by experiment.

Having thus described my invention, I claim:

1. Electron beam device comprising means for generating a hollow electron beam comprising an annular cathode, an accelerating anode having an annular aperture, a magnetic shield for said cathode and anode, an annular gap in said shield coaxial with the cathode and anode and aligned with the annular aperture in the anode to provide an exit aperture for the electron beam, means for generating magnetic flux across the annular gap in the shield to cause the electron beam traversing said gap to be subjected substantially exclusively to radial flux, cylindrical coaxial conductive elements aligned with the aixs of cathode, anode and flux gap and forming an annular passage for the emitted beam, and means for maintaining a potential difference between said coaxial elements.

2. Electron beam device comprising means for generating a hollow electron beam comprising coaxial magnetic structure having an annular gap at one end, an electron-emitting annular cathode within the magnetic structure and shielded thereby, an anode disposed within the magnetic structure intermediate the cathode and the annular gap in the shield, means for generating magnetic flux across the annular gap in the shield to cause the electron beam traversing said gap to be subjected substantially exclusively to radial flux uniformly distributed about the beam axis, thereby to impart to the electron substantially uniform tangential velocity about said beam axis, cylindrical coaxial conductive elements outwardly of the shield and axially disposed relative to the annular gap to define an annular wave guide passage for the electron beam emitted from the gap, and means for maintaining a potential difference between said coaxial elements to generate uniform inwardly-directed electrostatic forces on said electron beam along its axis.

3. Electron beam device comprising means for generating a hollow electron beam comprising coaxial magnetic structure containing electron emitting and accelerating means, said magnetic structure comprising a cylindrical shield, a central, axially directed member, an annular gap between the cylindrical shield and the central axially directed member at one end, the other end of the structure being closed to form a flux path between shield and central member, and means for generating magnetic flux across said annular gap, the electron emitting and accelerating means comprising a cathode and anode encircling the central axially directed member for directing an annular electron beam through the annular gap to cause the beam to be subjected substantially exclusively to radial magnetic flux relative to the beam axis, cylindrical coaxial conductive elements aligned with the axis of cathode, anode and flux gap and forming an annular passage for the emitted beam, and means for maintaining a potential difference between said coaxial elements.

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