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(54) **DOUBLE CUSP GYRO GUN**

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(52) **U.S. Cl.** **315/111.81**; 330/4; 315/1; 315/3.5

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(57) **ABSTRACT**

A gyrotron gun that generates gyrating electron beams in a controllable manner suitable for use in a wide range of gyro-amplifiers and gyro-oscillators is disclosed. The gyrotron comprises first and second means for abruptly changing a magnetic field and which means are positioned between first, second and third field coils. The field coils are operated so as to provide for a desired magnetic field profile that allows for the control of the parameters desired to provide for small-orbit, large-orbit, and linear modes of operation of the gyrotron gun. The gyrotron gun further comprises of a pair of bucking coils arranging near the cathode to independently control the axial velocity spread of the gyrating electron beam.

9 Claims, 7 Drawing Sheets

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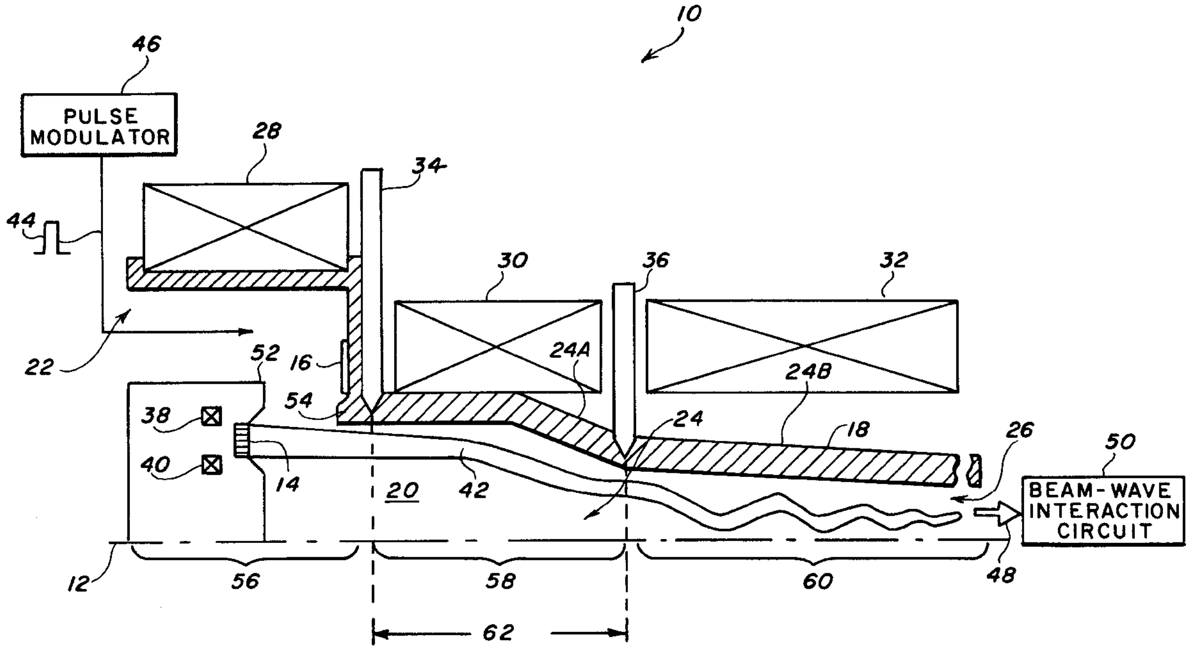

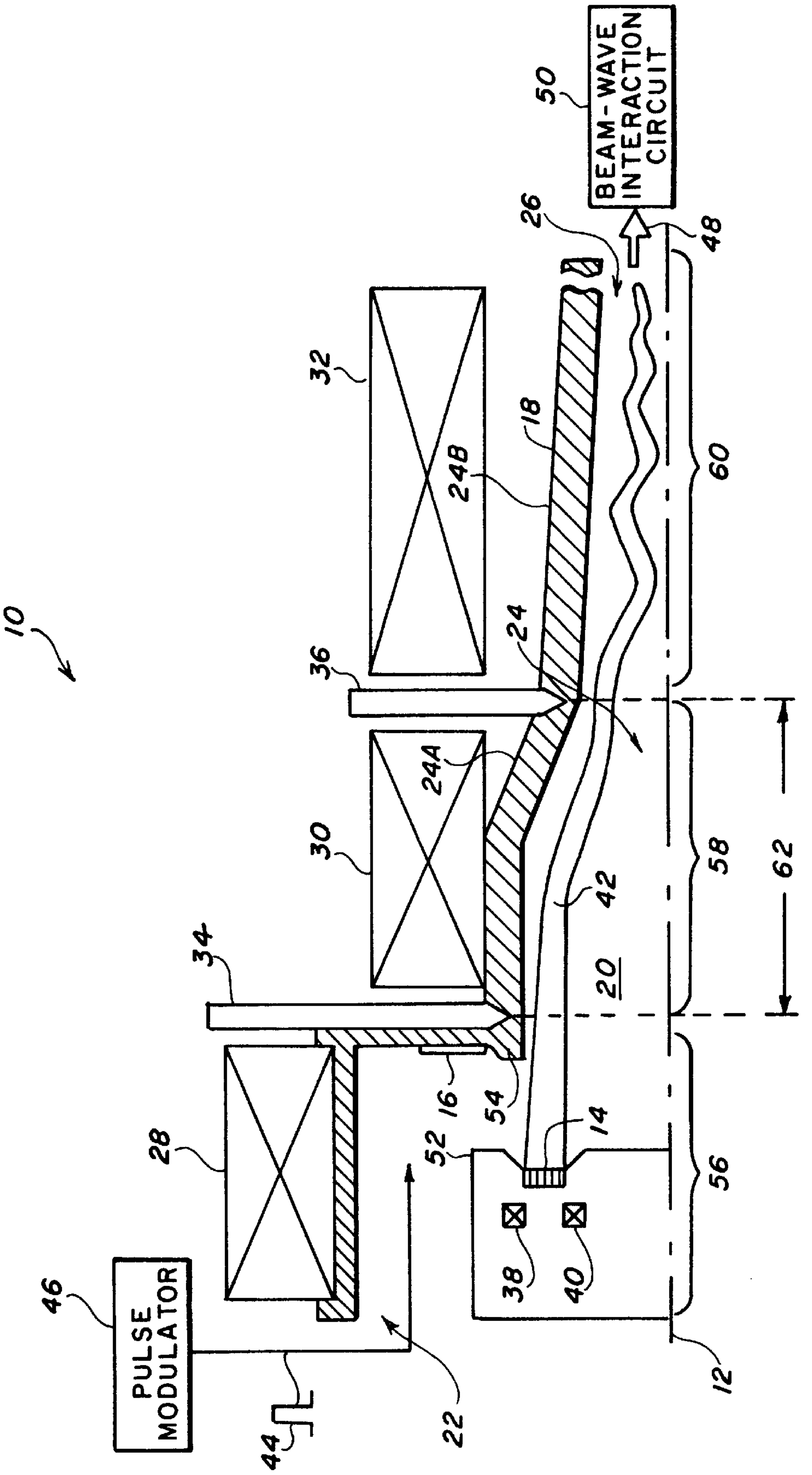
10
PULSE MODULATOR
46
44
22
28
34
16
54
52
14
38
40
12
56
20
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24A
36
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58
62
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BEAM-WAVE INTERACTION CIRCUIT

FIG. 1

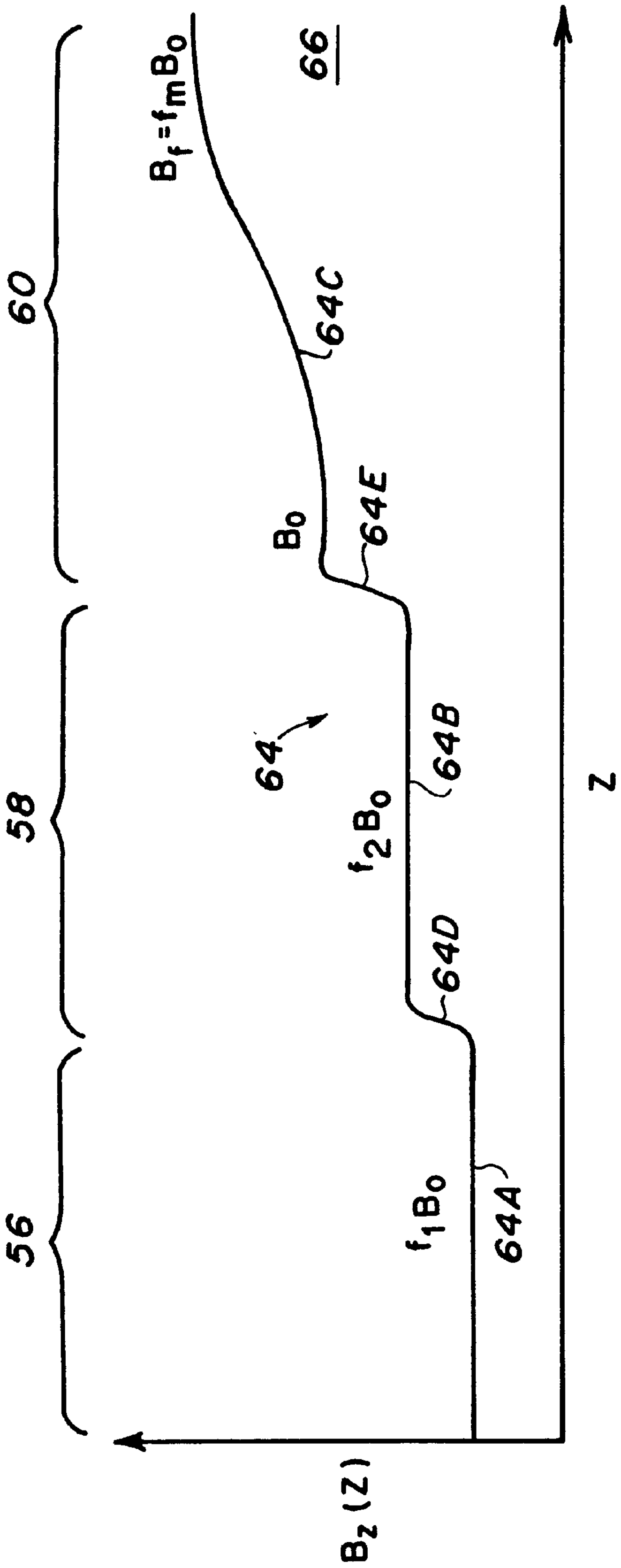

FIG. 2

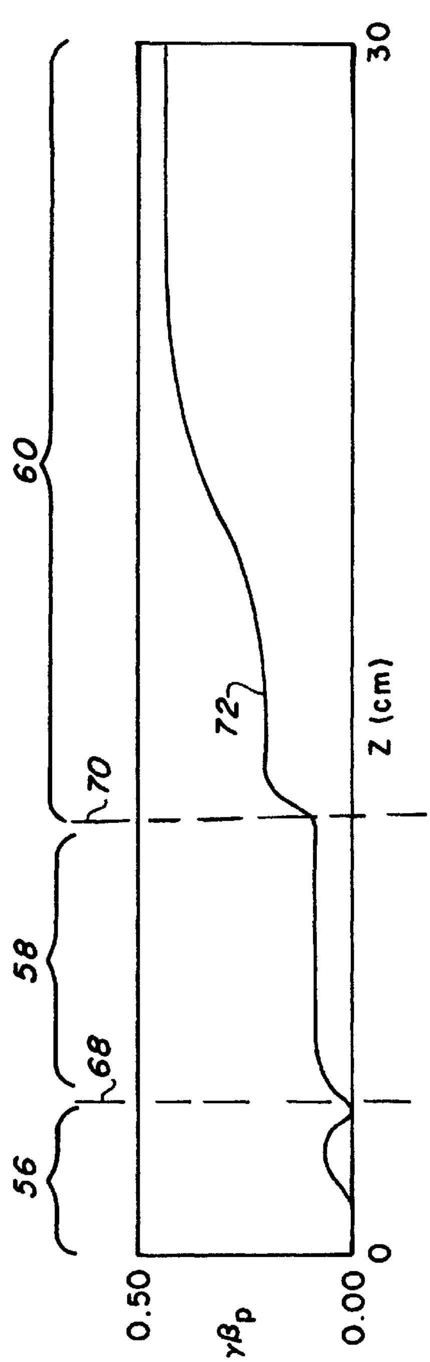

FIG. 3(A)

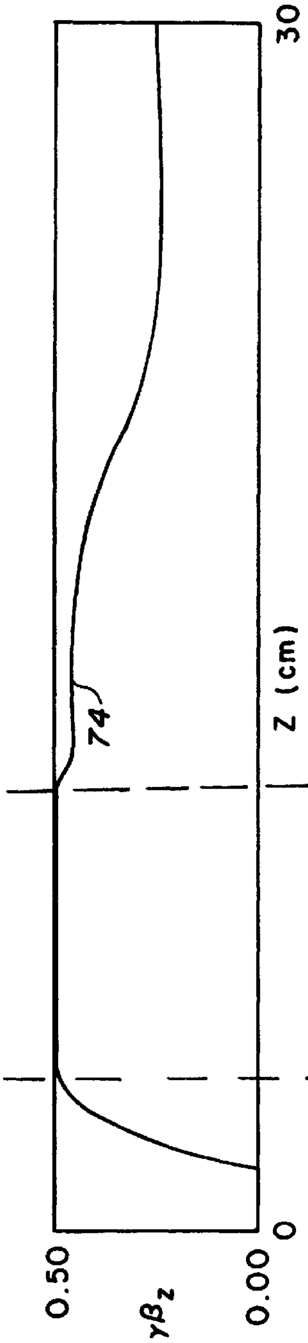

FIG. 3(B)

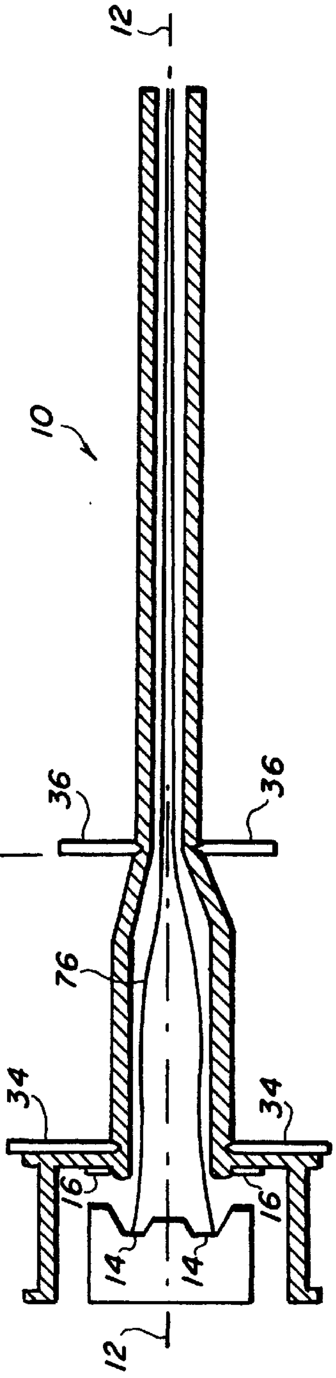

FIG. 3(C)

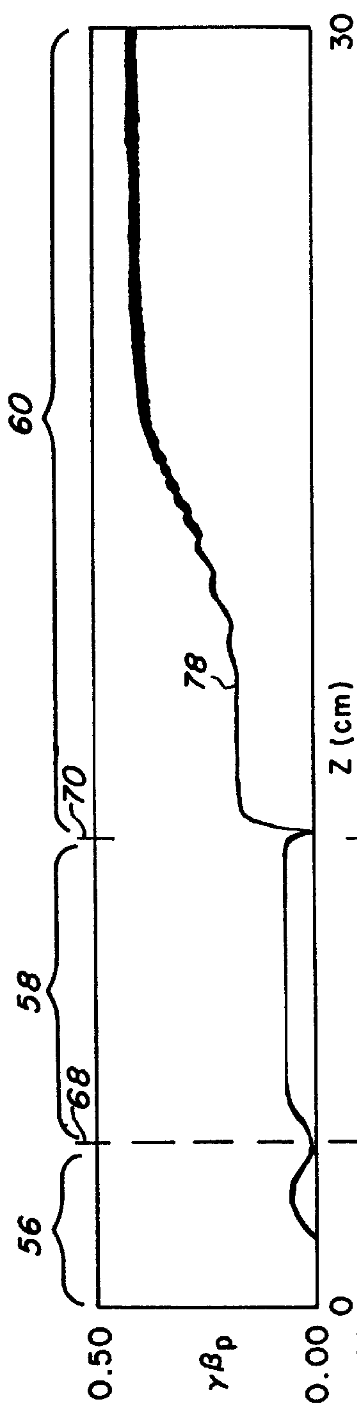

FIG. 4(A)

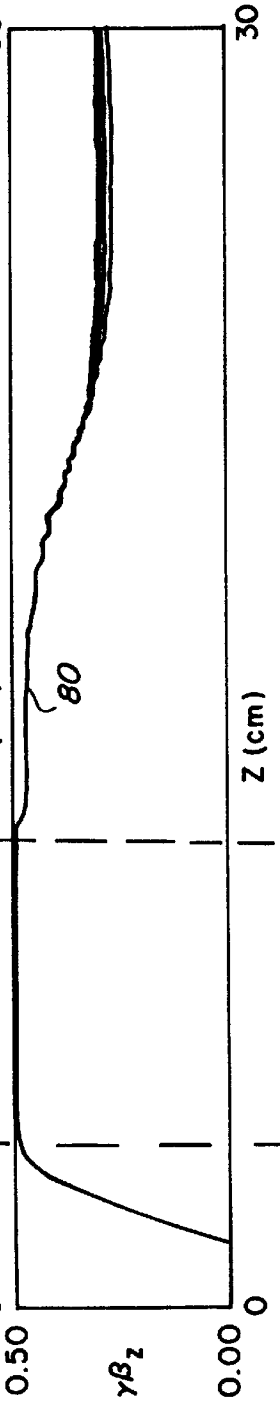

FIG. 4(B)

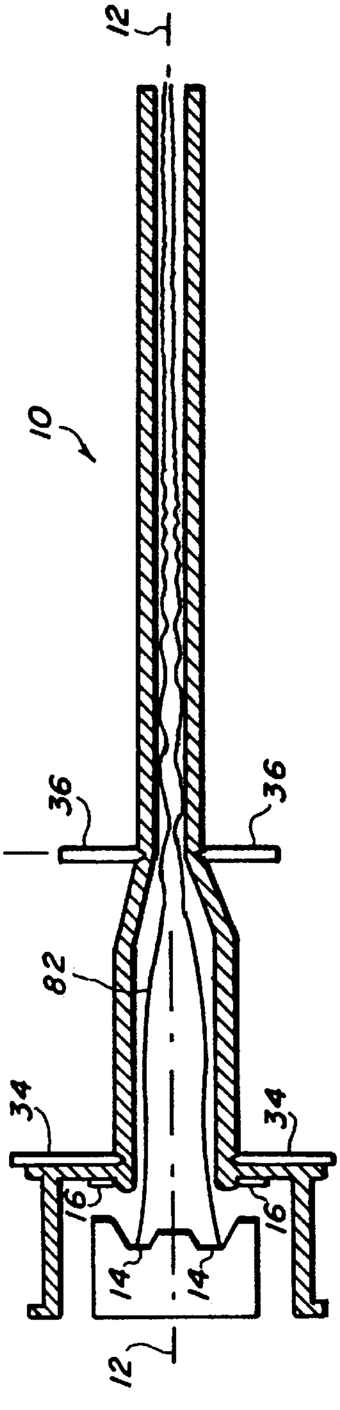

FIG. 4(C)

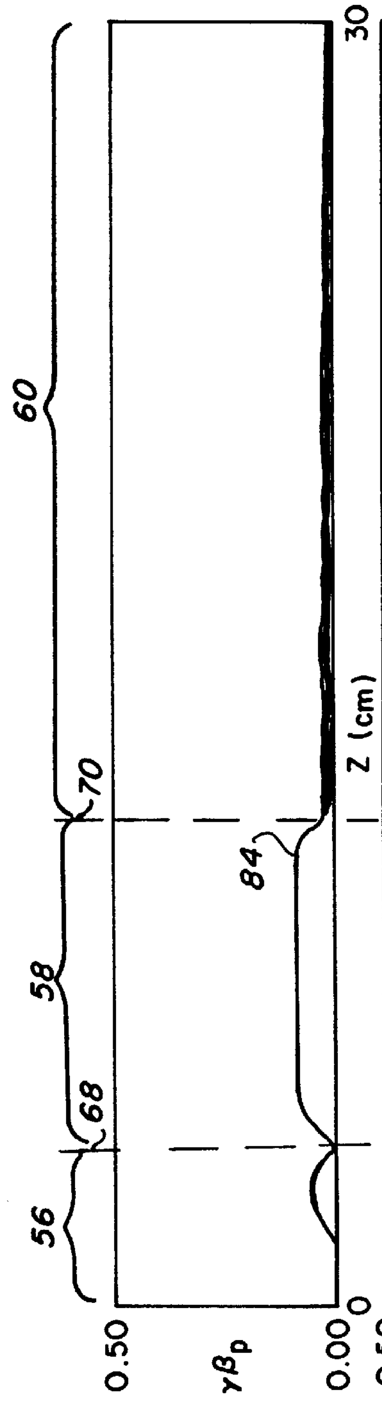

FIG. 5(A)

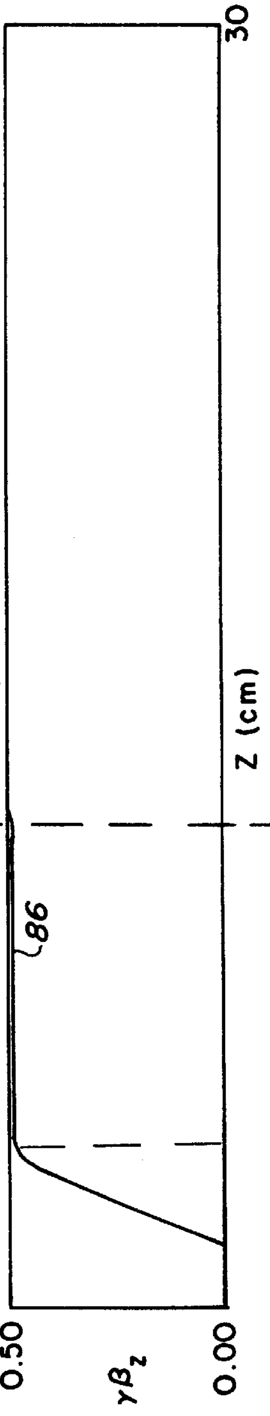

FIG. 5(B)

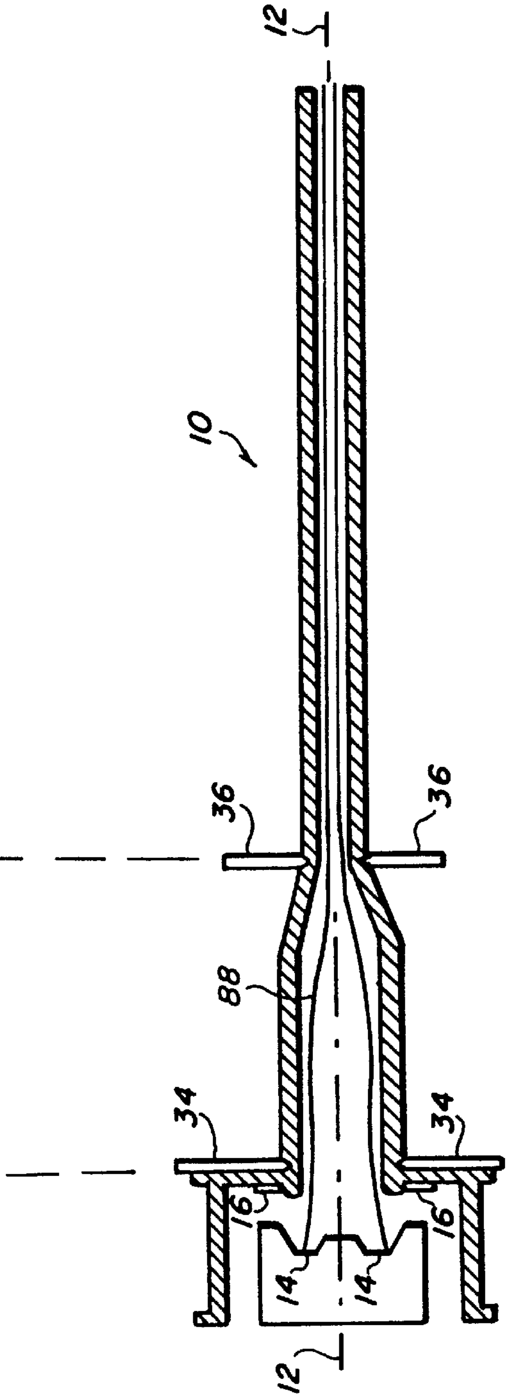

FIG. 5(C)

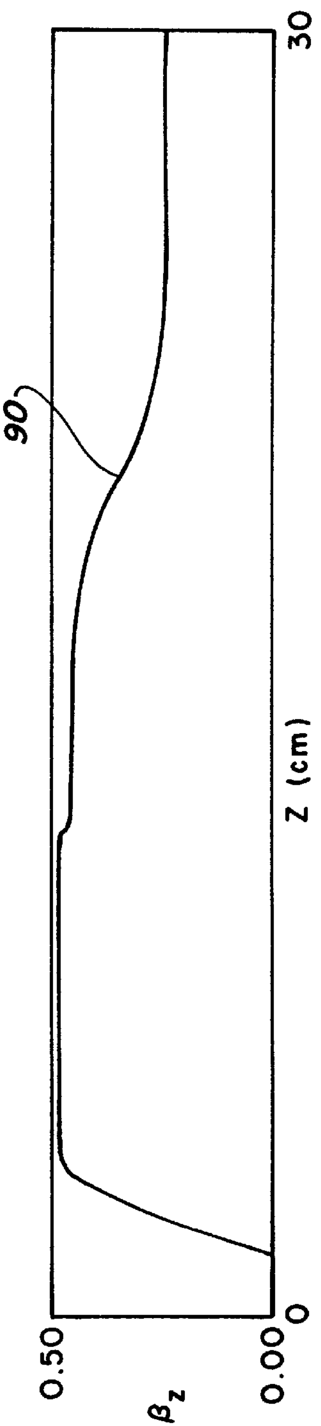

FIG. 6(A)

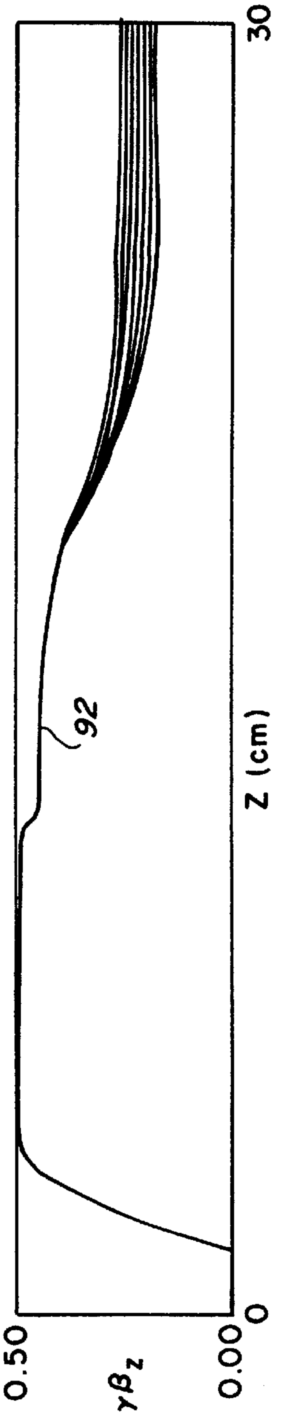

FIG. 6(B)

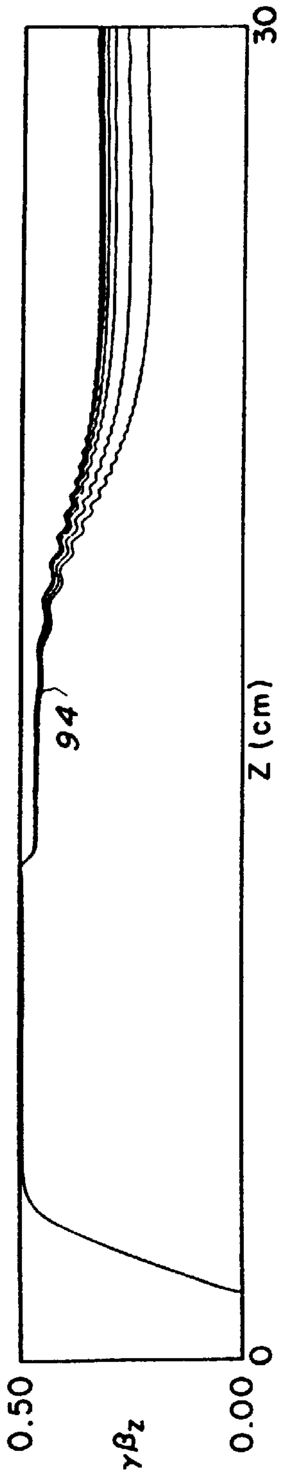

FIG.7(A)

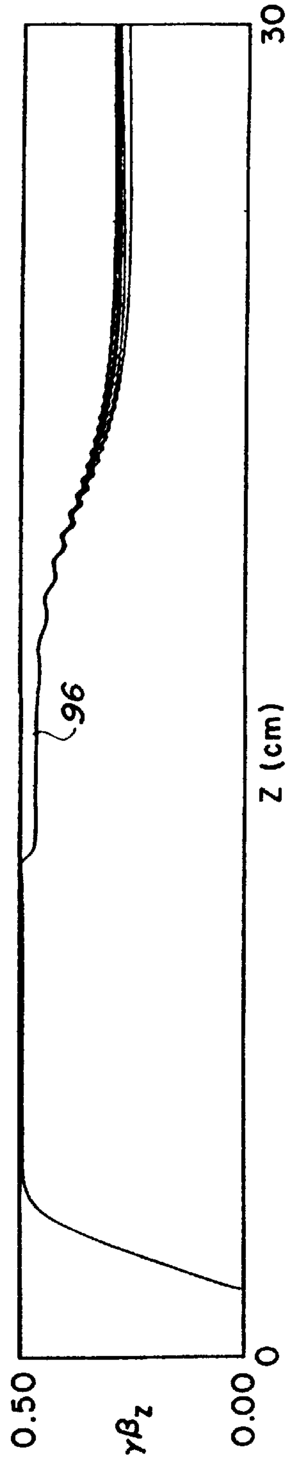

FIG.7(B)

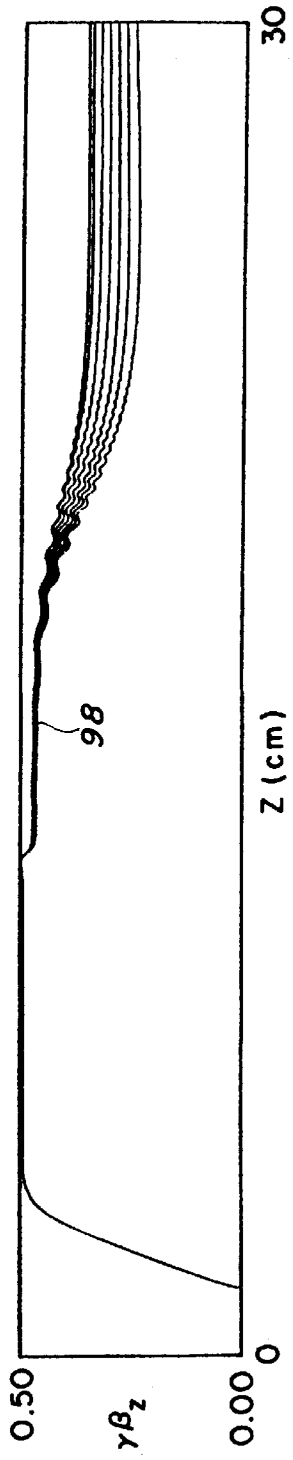

FIG.7(C)

DOUBLE CUSP GYRO GUN

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to the generation of electron beams for use in microwave generators and, more particularly, to the generation of gyrating electron beams in a controllable manner particularly suited for use in a wide range of gyro-amplifiers and gyro-oscillators.

2. Description of the Prior Art

Gyro-amplifiers and gyro-oscillators, which are commonly referred to as gyrotrons, require an electron beam that is different from that which is normally employed in linear microwave tubes, such as klystrons and traveling-wave tubes. In general, and as is known in the art, in gyrotrons microwave energy is extracted from the beam rotational energy through electron orbital phase bunching resulting from resonant interaction between the electron gyration and the transverse component of the electromagnetic waves contained in the interaction circuit, sometimes referred to as cyclotron resonant maser instability. To maximize this resonant interaction process and enhance the efficiency of the gyrotron, it is necessary for the bem forming system, also known as gyrotron gun or gyro-gun, to accomplish the following three factors: (a) form the gyrating electron beam with a large transverse-to-axial velocity ratio, $\alpha=v_\perp/v_z$ typically between one and two; (b) achieve and control the axial velocity, v_z, so as to have a low velocity spread in order to provide phase bunching stability; and (c) place the electron's beam guiding center, r_g, at the peak of the wave transverse electric field. The attainment of these three factors for all gyrotron device applications has not been accomplished by a single gyro-gun because of certain limitations.

First, the desired factors of the transverse-to-axial velocity ratio, $\alpha=v_\perp/v_z$, and the desired position of the electron's beam guiding center, r_g, primarily determine the electron orbital parameter which is different for various gyrotron applications. The selection of these desired factors in a gyro-gun to satisfy a gyrotron device requiring a particular orbit, such as, a small-orbit (non-axis encircling), may not be suitable when the same gyrotron gun is used for another application requiring a different type of orbit, such as, a large-orbit (axis-encircling).

Second, the desired parameter of controlling the axial velocity v_z spread is primarily of importance to the interaction circuit located at the output of the gyrotron gun and which circuit extracts microwave energy from the kinetic energy of the gyrating electron. The axial velocity spread is determined, in part, by the cathode of the gyrotron gun and the operation of the cathode. One approach to control the axial velocity v_z spread is to reduce the cathode's annulus width which, in turn, has the disadvantage of creating higher cathode loading. Another approach is to increase the cathode's mean radius which, in turn, has the disadvantage of increasing the overall size of the gyrotron gun which may not be desired for some applications.

FIRST PROBLEM

In relation to the first problem, several approaches, dictated by the parametric requirements in the beam-wave interaction region, have been used to provide for a desired small-orbit or large-orbit gyrotron beam. Although gyrotron guns designed for a particular parametric requirement serve well their intended function, once built employing existing beam-forming techniques, the gyrotron gun is often difficult to adjust in order to accommodate parameter changes that may arise from time to time. Various beam-forming devices determined by parametric requirements that have been developed prior to 1981 are well documented and summarized in a detailed report by Baird and Attard entitled "Gyrotron Gun Study Report" of the Naval Research Laboratory (NRL) Report TR-3-476 (1981). Each of the approaches prior to 1981 is suitable for use as a beam-forming system for a specific gyrotron device, depending upon the type of beam parameters required. For instance, the gyrotron gun, magnetic injection gun (MIG), originally conceived in the early 1960's, has been continuously used until the present time as a gyrotron beam-forming system and is particularly suited for small-orbit applications, but is not suited as a gyrotron beam-forming system having large-orbit applications. For a large-orbit gyrotron applications, a modified version of a magnetically shielded, space-charged limited Pierce gun (known in the art) has been proposed and is described by G. P. Scheitrum; R. S. Symons; and R. B. True, in the technical article entitled "Low Velocity Spread Axis Encircling Electron Beam Forming System," documented in the Technical Digest of Electron Devices Meeting, pp 743–746 (1989). Accordingly, although various beam-forming techniques are known to accommodate both small and large-orbit gyrotron devices, no one technique is known to accommodate both the small and large-orbit applications.

SECOND PROBLEM

In relation to the second problem, a primary cause of axial velocity v_z spread in gyrotron devices is due to the fact that electrons emitted from the cathode of the gyrotron gun at different radial positions enclose different amounts of magnetic flux, commonly referred to as canonical angular momentum spread. As previously mentioned, several approaches are known to reduce the axial velocity v_z spread and one of which is to reduce the cathode's annulus width. This is not however very practical, since this reduction creates a higher cathode loading factor, which has a tendency to overburden the cathode and, thereby, degrade its operational life characteristic. Another approach is to increase the cathode's mean radius. While this approach reduces velocity spread, it is accomplished at the expense of increasing the overall size of the gyrotron gun which may not be desired for some applications. An approach is to reduce the axial magnetic field on the surface of the cathode. An adaptation of this approach is to use a magnetic envelope and a magnetic center post as proposed by Chow and Pantell in the technical article "The Cyclotron Resonance Backward Wave Oscillator," documented in the proceedings of the IEEE, Vol. 48, pp. 1865–1867 (1980). In this technique, the center post carries the magnetic flux, while the magnetic envelope reduces the axial magnetic field on the cathode structure to virtually zero. However, a problem with this technique is that the magnetic center post is at essentially the same potential as that of the cathode; hence, practical implementations of this technique are prone to arcing between the center post and the anode due to large potential differences at their proximity. Moreover, this approach does not permit the flexibility of varying the beam canonical angular momentum spread to actively control the beam velocity spread for different applications of the gyrotron gun.

OBJECTS OF THE INVENTION

Accordingly, one object of the present invention, the double cusp gyro-gun, is to provide a gyrotron gun and a method of use thereof that have the flexibility of actively controlling the axial velocity v_z spread so as to accommodate different applications of the gyrotron gun.

Another object of the present invention is to provide a gyrotron gun and a method of use thereof that actively control the gyrating electron's beam transverse-to-axial velocity, $\alpha=v_\perp/v_z$, as well as the position of the electron's beam guiding center, r_g, so as to allow the gyrotron gun to be used for both small and large orbiting applications.

A still further object of the present invention is to provide a gyrotron gun and a method of use thereof that provide the flexibility for independently and simultaneously controlling the gyrating electron beam transverse-axial velocity ratio, $\alpha=v_\perp v_z$; the position of the electron's beam guiding center, r_g; as well as the spread of the axial velocity, v_z.

SUMMARY OF THE INVENTION

The invention is directed to a gyrotron gun that is operated to independently and simultaneously control a gyrating electron beam transverse-to-axial velocity ratio, $\alpha=v_\perp v_z$; the position of the electron's beam guiding center, r_g; as well as the spread of the axial velocity v_z, thereby, allowing the gyrotron gun to be used for large-orbit, small-orbit and even linear-beam modes of operation.

The gyrotron gun generates and forms a beam of electrons manifesting electron gyrating around a guiding center and having rotational energy. This is so that efficient phase bunching will result from a resonant interaction between the electron gyration and transverse component of the electromagnetic wave in the ensuing beam-wave interaction circuit. The gyrotron gun comprises first, second and third field coils and first and second means for establishing an abrupt change in a magnetic field. The field coils and the devices for establishing an abrupt change are arranged to form three regions. The field coils are operated so that each supply a predetermined strength of an axial magnetic field to allow for the control of the gyrating electron beam transverse-to-axial velocity ratio, $\alpha=v_\perp/v_z$; the position of the electrons beam guiding center r_g; and the spread of the axial velocity, v_z, so that the gyrotron gun can be used for small and large-orbit and even linear-beam modes of operation.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other objects, features and advantages of the present invention, as well as the invention itself, will become better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein like reference numerals designate identical or corresponding plots throughout the several views, and wherein:

FIG. **1** is a schematic illustrating an arrangement of the interrelated elements of the present invention;

FIG. **2** illustrates a plot of the magnetic profile of the present invention;

FIG. **3** is composed of FIGS. **3**(A), (B), and (C), wherein FIGS. **3**(A) and **3**(B) each illustrates a plot useful in the understanding in the large-orbit operation of the gyrotron gun of the present invention which is generally illustrated in FIG. **3**(C);

FIG. **4** is composed of FIGS. **4**(A), (B), and (C), wherein FIGS. **4**(A) and **4**(B) each illustrates a plot useful in the understanding of the small-orbit operation of the gyrotron gun of the present invention which is generally illustrated in FIG. **4**(C);

FIG. **5** is composed of FIGS. **5**(A), (B), and (C), wherein FIGS. **5**(A) and **5**(B) each illustrates a plot useful in the understanding of the linear-mode operation of the gyrotron gun of the present invention which is generally illustrated in FIG. **5**(C);

FIG. **6** is composed of FIGS. **6**(A), and (B), each of which illustrates a plot related to the axial velocity, v_z, spread associated with the large-orbit operation of the gyrotron gun of the present invention;

FIG. **7** is composed of FIGS. **7**(A), (B), and (C), each of which illustrates a plot related to the axial velocity, v_z, spread associated with the small-orbit operation of the gyrotron gun of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings, FIG. **1** illustrates an arrangement of elements of a gyrotron gun **10** having a centerline **12**. The gyrotron gun **10** is preferably circular so that the arrangement of the elements of FIG. **1** is actually also below the centerline **12**.

The gyrotron gun **10** generates gyrating electron beams in a controllable manner suitable for a wide range of applications. The gyrotron gun **10** has a predetermined operating period, sometimes referred to as a gyro-period, with a corresponding predetermined wavelength. The gyrotron device **10** may also be referred to herein as a double-cusp gyro gun **10**. The gyrotron device **10** generates and forms a beam of electrons manifesting electron gyrating around a guiding center and having rotational energy. This is so that efficient phase bunching will result from a resonant interaction between electron gyration and a transverse component of electromagnetic waves contained in the ensuing beam-wave interaction circuit **50**. The resonant interaction is determined by three factors which are: **(1)** the transverse-to-axial velocity ratio, $\alpha=v_\perp/v_z$, of the gyrating electron beam; **(2)** the position of the electron's beam guiding center, r_g, and **(3)** the spread of the axial velocity v_z of the electron beam. The gyrotron device **10** of FIG. **1** comprises a plurality of elements each having a reference number all of which are given in Table 1.

TABLE 1

REFERENCE NO.	ELEMENT
14	Cathode
16	Anode
18	Vacuum Envelope
20	Electron Tunnel
22	Entrance Section of Electron Tunnel 20
24	Intermediate Section of Electron Tunnel 20
26	Exit Section of Electron Tunnel 20
28	First Field Coil
30	Second Field Coil
32	Third Field Coil
34	First Cusp Member
36	Second Cusp Member
38	First Bucking Coil
40	Second Bucking Coil
42	Electron Beam

The cathode **14** is preferably of a thermionic type or any other electron emitting type and also preferably has an annular shape. As is known, the thermionic cathode **14**, when subjected to a relatively high-voltage pulse **44**, generated from a conventional power modulator **46** and present at the entrance section **22**, allows the extraction therefrom of an electron beam **42** which is accelerated toward a higher potential anode **16**, also located in the entrance section **22**. The electron beam **42** moves along the full length of an electron tunnel **20** and is extracted from the exit section **26** thereof, as shown by arrow **48**, into a beam-wave interaction circuit **50**, known in the art. The beam-wave interaction circuit **50** converts the kinetic energy of the electron beam **42** into microwave energy.

Also as is known in the art, and as is shown in FIG. **1**, the anode **16** (preferably of an annular shape) is offset from the cathode **14** and protrusions **52** and **54** are interposed therebetween allowing the electron beam **42** attracted to the anode **16** to be diverted away therefrom and directed toward the intermediate section **24**.

The vacuum envelope **18**, illustrated by a cross-hatch representation in FIG. **1**, forms the electron tunnel **20** having the entrance section **22**, the intermediate section **24** having first and second portions **24A** and **24B**, and the exit section **26**. The vacuum envelope **18** is preferably formed of a non-magnetic metallic material and arranged in a manner known in the art.

The first, second and third field coils **28**, **30**, and **32**, respectively, are preferably formed of a metallic material, known in the art, and are arranged so that the first field coil **28** is situated near the entrance section **22** and the second and third field coils **30** and **32** are situated at the intermediate section **24**. The field coils **28**, **30** and **32**, as well as the bucking coils **38** and **40**, are indicated in FIG. **1** with an X symbol.

The first and second cusp devices **34** and **36** preferably comprise a high permeability material, such as soft iron. The term "cusp" is known in the art and is meant to represent that the device provides for an abrupt change in a magnetic field as the magnetic field passes through the cusp device. The arrangement of the cusp devices **34** and **36**, relative to the field coils **28**, **30** and **32**, provide for three different operating regions which are of particular importance to the present invention.

The first cusp device **34** is interposed between the first and second field coils **28** and **30**, respectively. The second cusp device **36** is interposed between the second and third field coils **30** and **32**, respectively. The first field coil **28** and the first cusp device **34** establish a first operating region **56**. Further, the first cusp device **34** and the second cusp device **36**, both in combination with the second field coil **30**, establish a second operating region **58**. Further, the second cusp device **36** and the third field coil **32** establish a third operating region **60**. The first (**56**), second (**58**), and third (**60**) operating regions are respectively herein termed the diode region **56**, the double-cusp region **58**, and the adiabatic compression region **60**. The first cusp device **34** and the second cusp device **36** are spaced apart, as shown in FIG. **1**, from each other by a distance **62** which preferably corresponds to one-half of the operating gryo-period of the gyrotron device **10**.

The first and second bucking coils **38** and **40** are supplied with opposite currents and are located near, but preferably behind, the cathode **14**, as shown in FIG. **1**, so as to reduce or even cancel the axial magnetic field on the cathode surface in a manner as to be further described hereinafter with reference to FIGS. **6** and **7**.

The parameters of the electron beam **42** formed and generated by the gyrotron gun **10** are controlled by the field strength of the axial magnetic fields applied to the regions **56**, **58** and **60** by way of the first, second and third field coils **28**, **30** and **32**, respectively. The operation of the gyrotron device **10** is primarily determined by a magnetic profile **64**, which may be further described with reference to FIG. **2**.

FIG. **2** illustrates the magnetic profile **64** of the electron beam **42** as it passes through and is developed therein by the diode, double-cusp and adiabatic compression regions **56**, **58** and **60**, respectively, and propagates to the tip **66** of the exit section **26**, whereby the kinetic energy of the electron beam **42** is extracted by the beam-wave interaction circuit **50** to provide microwave energy therefrom. FIG. **2** has a horizontal axis, given by the quantity, z, representative of the axial position of the electron beam **42** as it moves along the gyrotron device **10**, as generally illustrated in FIG. **1**. Further, FIG. **2** has a vertical axis represented by the quantity B_z (Z) which is the average axial magnetic field enclosed by the electron beam **42**.

The magnetic profile **64** comprises a first section **64A**, a second section **64B**, and a third section **64C**, respectively, associated with regions **56**, **58** and **60**, and respectively represented by the quantities f_1B_0, f_2B_0 and B_0 and $B_f=f_mB_0$, wherein the quantities B_0 and $B_f=f_mB_0$ are present at the initial and terminal portions, respectively, of the third section **64C**. The cusp devices **34** and **36** (see FIG. **1**) impart a rotation to the electron beam **42** which impartations are generally illustrated in FIG. **2** by ramping portions **64D** and **64E** respectively.

In general, the usage of the first and second cusp devices **34** and **36**, the selection of the quantities f_1B_0, f_2B_0, B_0 and f_mB_0, determined by the operation of the first, second and third field coils **28**, **30** and **32** respectively, as well as the operation of the bucking coils **38** and **40**, provide for independent and simultaneous control of the three factors: (**1**) the transverse-to-axial velocity ratio, $\alpha=v_\perp/v_z$; (**2**) the position of the electron's beam guiding center, r_g; and (**3**) the axial velocity spread, all of which three factors have been previously discussed in the "Background" section. The operation and method of the present invention provide the capability to optimize the energy conversion in the beam-wave interaction circuit **50** without modifying the mechanical features of the double cusp gyro gun **10**. More particularly, once the physical features, composition and arrangement of the elements of the double-cusp gyro gun **10** are selected, they do not need to be changed, but rather only the amount of current applied to the field coils **28**, **30** and **32** and bucking coils **38** and **40** need to be adjusted to control the operating parameters of the double-cusp gyro gun **10**. Thus, problems and limitations associated with prior art beam-forming practices, discussed in the "Background" section, are avoided.

The trajectory of the electrons forming beam **42**, after extraction from the cathode **14**, is dictated primarily by the magnetic field profile **64**, via Lorentz force. Evaluation of such a trajectory is based on an idealized theoretical model which employs the principle of canonical angular momentum conservation. The canonical angular momentum, P_θ, of an electron charge q, mass m and energy γ, at radius r, axial position z, and angular velocity v_θ may be represented by expression 1 given below:

$$P_\theta=\gamma mrv_\theta-qrA_\theta(r,z) \tag{1}$$

The term P_θ represent a conserved quantity in an azimuthally symmetric system. The vector potential, A_θ(rz), for the total magnetic field profile **64**, may be estimated by expression 2 given below:

$$A_\theta(r,z)=\tfrac{1}{2}rB_z(z) \tag{2}$$

where B_z (z) is the average axial magnetic field enclosed by an electron forming part of the electron beam **42**. With the quantity $\omega_{c2}\equiv(qB_z)/(\gamma m)$, the canonical angular momentum may be represented by expression 3 given below which is treated as a conserved quantity throughout the entire gyrotron device **10**:

$$P_\theta=(\gamma m)[rv_\theta-½r^2\omega_{cz}(z)] \tag{3}$$

As previously mentioned with reference to FIG. **2**, the first cusp device's **34** transition field imparts an angular velocity to the electron beam **42**, via the $v_z \times B_r$ Lorentz force term, hence, initiating cyclotron motion within the double-cusp region **58**. From conservation of the canonical angular momentum, it can be shown that the electron perpendicular velocity in the double-cusp region **58** may be represented by expression 4 given below:

$$v_{\perp 1+}=½(1-f_1)f_2\omega_{co}r_1 \tag{4}$$

where r_1 is assumed to be the electron radial position at the cathode **14** and also at the first cusp device **34**; f_1 and f_2 are the axial magnetic field quantities respectively related to the diode region **56** and the double cusp region **58**, and ω_{co} is the electron angular cyclotron frequency at the start of the adiabatic compression region **60**. More particularly, with reference to FIG. **2**, the quantities f_1 and f_2 are respectively included in sections **64**A and **64**B of magnetic profile **64** and the quantity ω_{co} is included in the peak of the ramp portion **64**E of the magnetic profile **64**. It should be pointed out that the electron perpendicular motion immediately after the first cusp device **34** is primarily azimuthal, since the electron motion has assumed to be paraxial in the diode region **56**. Based on this assumption, the electron position at the second cusp device **36** where the electron radial velocity vanishes may be represented by the expression 5 given below:

$$r_2=f_1r_1 \tag{5}$$

As previously mentioned, the distance **62** (see FIG. **1**) between the two cusp devices **34** and **36** is preferably and precisely one-half of a gyro-period. For such a preferred distance **62**, the electron motion in the double-cusp region **58** is that of a small-orbit (non-axis encircling) gyration wherein its guiding center may be represented by expression 6 given below:

$$r_{g1+}=½(1+f_1)r_1 \tag{6}$$

At the second cusp device **36**, the radial magnetic field thereat imparts an additional velocity thrust on the electron beam (see FIG. **2**, in particular, ramp portion **64**E). As further seen in FIG. **2**, the field strength at the exit of the double-cusp region **58** is B_0 which is illustrated near the termination of the ramp portion **64**E which corresponds to the second cusp device **36** transition region of the profile **64**. Upon leaving the transition region of the second cusp device **36**, the perpendicular velocity may be represented by expression 7 given below:

$$V_{\perp 2+}=½(f_1-f_2)\omega_{co}r_1 \tag{7}$$

The guiding center region at the beginning of the adiabatic compression region **60** may be represented by expression 8 given below:

$$\begin{aligned} r_{g2+} &= r_2-\frac{V_{\perp 2+}}{\omega_{co}} \\ &= 1/2(f_1+f_2)r_1 \end{aligned} \tag{8}$$

It should be noted, and as will be further discussed hereinafter with reference to FIGS. **6** and **7**, that for a particular case wherein $f_1=-f_2$, there is no beam guiding center spread. The ratio of the perpendicular velocity to axial velocity is found from energy conservation and may be represented by expression 9 given below:

$$\begin{aligned} \alpha_{2+} &= \frac{v_{\perp 2+}}{[v_o^2-v_{\perp 2}+^2]^{1/2}} \\ &= \left[\frac{1/4(f_1-f_2)^2\omega^2{}_{co}r_1^2}{v_o^2-1/4(f_1-f_2)^2\omega_{co}^2r_1^2}\right]^{1/2} \end{aligned} \tag{9}$$

where v_o is the electron velocity at the exit of the diode region **56**.

From expressions (7) and (8) it may be shown that by properly selecting the magnetic field profiles, in particular the quantities f_1 and f_2, a wide variety of beam configurations can be generated and are shown in Table 2.

TABLE 2

QUANTITIES f_1 AND f_2 OF MAGNETIC FIELD PROFILE 64	BEAM CONFIGURATION
$(f_1 = f_2)$	Linear Beam
$(\lvert f_1\rvert = -\lvert f_2\rvert)$	Large-Orbit
$(f_1 \neq f_2)$	Small-Orbit

The present invention also provides a means to control independently the beam guiding center r_g, and the transverse-to-axial $\alpha=v_\perp/v_z$ via selecting the sum, f_1+f_2, and the difference, f_1-f_2, of quantities of diode region **56** and of double-cusp region **58**.

Finally, after the adiabatic compression region **60** alters the axial field strength from B_0 to $B_f=f_mB_0$, the guiding center r_g sometimes referred to as r_{gf}, and transverse-to-axial velocity ratio α, sometimes referred to as α_f, at the tip **66** (see FIG. **2**) of the gyrotation device **10** as it enters the beam-wave interaction circuit **50** may be respectively represented by expressions 10 and 11 given below:

$$r_{gf}=\frac{1}{f_m^{1/2}}r_{g2+}=\frac{f_1+f_2}{2f_m^{1/2}}r_1 \tag{10}$$

$$\alpha_f=\left[\frac{(\alpha_{2+})^2f_m}{1+(1-f_m)(\alpha_{2+})^2}\right]^{1/2}=\left[\frac{1/4f_m^{-1}(f_1-f_2)^2\omega_{cf}^2r_1^2}{v_0^2-1/4f_m^{-1}(f_1-f_2)^2\omega_{cf}^2r_1^2}\right]^{1/2} \tag{11}$$

where ω_{cf} is the angular cyclotron frequency at the r_f interaction region of the beam-wave interaction circuit **50**.

In addition to the relationships given by the expressions 10 and 11 for terms normally referred to as r_g and α, for a gyrotron gun **10** satisfying the requirements that the distance **62** between the two cusp devices **34** and **36** (see FIG. **1**) being one-half of a gyro-period in length, the gyrotron device **10** further has interrelationship between the quantities f_2 and f_m. That is, the ratio f_2/f_m is determined by both f_2B_0 (half gyro-period criterion), and f_mB_0 (interaction circuit **50** requirement). Consequently, for a given value of the parameter B_f, it is possible to adjust the guiding center, r_g, and the transverse-to-axial velocity ratio, α, independently by adjusting the quantities f_1 and f_2. More particularly, the employment of the double-cusp region **58** in the gyrotron gun **10** permits the independent control over the parameters (α, r_g, and B) in a relatively simple manner by means of selecting and adjusting the quantities f_1, f_2, and f_m, hence, achieving more flexibility with less complexity as compared to prior art beam-forming apparatuses.

It is important to emphasize, however, that the necessity that the radial velocity vanish (see expression (5)) at the second cusp device **36** (hence, the half-gyro-period length criterion discussed for distance **62**) is not really needed for small-orbit operations of the gyrotron gun **10**. However, for linear and large-orbit operations of the gyrotron gun **10**, it is desired that the radial velocity be zero (see expression (5)) at the second cusp device **36** so as to ensure that beam ripple (scalloping) is minimized.

It should now be appreciated that the practice of the present invention provides for a gyrotron gun **10** employing a first and second cusp devices **34** and **36**, respectively, that allow for the ability to provide independent and simultaneous control of the quantities of expressions **10** and **11**, that is, guiding center r_g and transverse-to-axial velocity ratio α respectively. Furthermore, it should be appreciated that the control of the guiding center r_g and transverse-to-axial velocity ratio α is accomplished simply by varying the magnetic field profile **64** shown in FIG. **2** and is done so without modifying or altering any physical features of the gyrotron gun **10**.

In the practice of the present invention, a beam optic simulation study was performed. In the study, the mechanical features of the gyrotron gun **10** remain fixed and only the magnetic field profile **64** was varied to affect various final beam parameters that allowed the gyrotron gun **10** to provide small and large-orbits and linear beam modes of operation. The magnetic field profiles were obtained from a magnetic design code, POISSON, by specifying the currents for the electric field coils **28**, **30** and **32**, and the bucking coils **38** and **40** all shown in FIG. **1**. The POISSON is a well-known magnetic design code developed by Los Alamos National Laboratories. The magnetic field profiles obtained from the POISSON magnetic design were used as inputs to a MAGIC code to perform beam optics simulation. The MAGIC code is a self-consistent, two-and-one-half dimensional, particle-in-cell code developed by Mission Research Corporation and is known in the art. The study performed for the gyrotron device **10** resulted in different beam types exemplified by three beam optic cases shown in FIGS. **3**, **4** and **5** and respectively representative of a large-orbit operation, a small-orbit operation, and a linear beam mode of operation.

FIG. **3** is composed of FIGS. **3**(A), (B) and (C), wherein FIGS. **3**A and **3**B respectively illustrates the beam perpendicular $\gamma\beta_p$ and axial momenta $\gamma\beta_z$, normalized by the speed of light as a function of axial distance. A gyrotron gun **10** is generally illustrated in FIG. **3**(C), but without the placement of the field coils **28**, **30** and **32** thereon. FIGS. **3**(A), (B) and (C) are all interrelated to the diode region **56**, double-cusp region **58**, and the adiabatic compression region **60** (shown above FIG. **3**(A)) and the interrelationship thereof is shown by the use of dimensional lines **68** and **70**. FIG. **3** shows a beam perpendicular momentum plot **72** (FIG. **3**(A), an axial momentum plot **74** (FIG. **3**(B)) and a beam trajectory **76** (FIG. **3**(C)), all corresponding to the usage of the gyrotron gun **10** for a large-orbit operation, where the resulting beam trajectory **76** is rotated around the gyrotron axis **12** (axis encircling). The large-orbit operation of FIG. **3** was accomplished by the use of a 60 kV, 4.4-A electron beam, which was also used in the operations illustrated in FIGS. **4** and **5**.

FIG. **4** is similar to FIG. **3** and illustrates a plot **78** of the beam perpendicular momentum quantity $\gamma\beta_p$ (FIG. **4**(A)), a plot **80** of the axial momentum quantity $\gamma\beta_z$ (FIG. **4**(B)) and a beam projectory **82** (FIG. **4**(C)), all related to the small-orbit operation of the gyrotron gun **10**. As is known in the art, for a small-orbit operation, the electrons comprising electron beam **42** of FIG. **1** are rotated around and off-axis from its guiding center r_g.

FIG. **5** is similar to both FIGS. **3** and **4** and illustrates a plot **84** of the beam perpendicular momentum quantity $\gamma\beta_p$ (FIG. **5**(A)), a plot **86** of the axial momentum quantity $\gamma\beta_z$ (FIG. **5**(B)), and a beam projectory **88** (FIG. **5**(C)), all related to a linear-beam mode of operation of the gyrotron gun **10**. The linear-beam operation is one in which the beam is non-rotating. It should be noted in FIG. **5**(A) that the perpendicular momentum $\gamma\beta_p$ essentially vanishes after the second cusp device **36** (not shown) that separates the double-cusp region **58** from adiabatic compression region **60**.

It should now be appreciated that the practice of the present invention provides for a gyrotron gun **10** wherein the quantities given in Table 2 may be selected so as to provide for a small-orbit, large-orbit or linear modes of operation.

As mentioned in the "Background" section, the energy conversion efficiency of the beam-wave interaction circuit **50** is dependent upon the beam velocity spread. As further discussed in the "Background" section, various approaches were used to control the beam velocity spread, but none yielded complete success. The present invention accomplishes such control by the use of the bucking coils **38** and **40**. More particularly, the bucking coils **38** and **40** are supplied with opposite currents and preferably located behind the cathode **14** so as to reduce or even cancel the axial magnetic field on the surface of the cathode **14** and, hence, the canonical angular momentum spread. This technique permits the active control of the beam velocity spread and also avoids potential arcing problems discussed in the "Background" section. Further, this technique provides the gyrotron gun **10** with the ability to operate in the large and small-orbit modes of operation which may be further described with reference to FIGS. **6** and **7** illustrating results that were obtained from the aforementioned particle simulation study, already described with reference to FIGS. **3**, **4** and **5**.

FIG. **6** is composed of FIGS. **6**(A) and **6**(B) both of which show the electron beam **42** normalized in axial momentum vs axial distance for two separate large-orbit simulations, similar to each other except for the amount of canonical angular momentum P_θ spread. FIG. **6**(A) illustrates the normalized axial momentum $\gamma\beta_z$ shown by plot **90**, wherein the bucking coils **38** and **40** are completely activated (no P_θ spread). Conversely, FIG. **6**(B) illustrates the normalized axial momentum $\gamma\beta_z$ shown by plot **92** resulting from the bucking coils **38** and **40** being turned-off, thereby, providing for an axial velocity spread of 11.2% at α=1.83. The large velocity spread indicates that the P_θ quantity is one of the main contributors that cause for velocity spread in large-orbit beams.

FIG. **7** is composed of FIGS. **7**(A), (B) and (C) all related to small-orbit operations of gyrotron device **10**. FIG. **7**(A), (B) and (C) respectively illustrates plots **94**, **96** and **98**, wherein, respectively, the bucking coils **38** and **40** are fully turned on, the bucking coils **38** and **40** are partially turned on, and the bucking coils **38** and **40** are turned off. The plot **94** indicates a final velocity spread of 3.9% at α=1.4, the plot **96** indicates a final velocity spread of 1.6% at α=1.35, and the plot **98** indicates a final velocity spread of 14.5% at α=1.2. A comparison between plots **94**, **96** and **98** reveals that the gyrotron device **10**, in particular, the bucking coils **38** and **40** act as a means for controlling the velocity spread related to the small-orbit beam operation, and also that this velocity spread may be advantageously adjusted for various applications by the practice of this invention.

It should now be appreciated that the practice of the present invention provides for a means for controlling the axial velocity v_z spread, the gyrating electron transverse-to-axial velocity ratio α, as well as the electron beam guiding center, r_g. These factors are controlled by the diode region **56**, the double-cusp region **58**, and the adiabatic compression region **60** carrying an adjustable and predetermined magnetic profile **64**.

It should therefore readily be understood that many modifications and variations of the present invention are possible within the purview of the claimed invention. It is, therefore, to be understood that, within the scope of the appended claims, the invention may be practiced otherwise than as specifically described.

What is claimed and desired to be secured by Letters Patent of the United States is:

1. A system for generating and forming a beam of electrons comprising:

(a) a vacuum envelope forming a tunnel having entrance, intermediate and exit sections with the intermediate having first and second portions;

(b) first, second and third field coils with the first being situated at said entrance section and the second and third being situated at said intermediate section;

(c) first and second means for establishing an abrupt change in a magnetic field, said first and second abrupt change means being respectively interposed between said first and second field coils and said second and third field coils, said first field coil and said first abrupt change means comprising a first operating region, said second field coil and said first and second abrupt change means comprising a second operating region and said third field coil and said second abrupt change means comprising a third operating region;

(d) a cathode located in said entrance section and capable of emitting a beam of electrons when subjected to the presence of a relatively high voltage pulse; and

(e) an anode located in said entrance section and spaced apart from said cathode and capable of attracting said beam of electrons.

2. The system for generating and forming an electron beam according to claim **1** further comprising a pair of bucking coils located near said cathode.

3. The system for generating and forming an electron beam according to claim **1** further comprising an interaction circuit connected to said exit portion and extracting microwave energy from said beam of electrons.

4. The system for generating and forming an electron beam according to claim **1**, wherein said cathode is thermionic or comprises other electron emitting devices.

5. The system for generating and forming an electron beam according to claim **1**, wherein said cathode and said anode both have an annular shape.

6. The system for generating and forming an electron beam according to claim **1**, wherein said cathode and anode are offset from each other and have protrusions interposed therebetween so that said beam of attractable electrons are diverted away from said anode and directed toward said intermediate section.

7. The system for generating and forming an electron beam according to claim **1**, wherein said vacuum envelope, said first, second and third field coils and said first and second means for establishing an abrupt change in a magnetic field comprise a gyrotron device having a predetermined operating period with a corresponding predetermined wavelength and said first and second means for establishing an abrupt change are spaced apart from each other by a distance corresponding to one-half of said predetermined wavelength.

8. A method using a gyrotron gun having a cathode that emits a beam of electrons when subjected to the presence of a relatively high voltage pulse and an anode spaced apart from said cathode and energized with respect to said cathode so that said beam of electrons are attractable toward said anode, said gyrotron gun generating and forming a beam of electrons manifesting electron gyrating around a guiding center and having rotational energy, said beam-forming being determined by at least two factors: (1) the transverse-to-axial velocity ratio, α, of the gyrating electron beam; and (2) the position of the electron's mean guiding center, r_g, said method comprising the steps of:

(a) providing a vacuum envelope that forms a tunnel having entrance, intermediate and exit sections with the intermediate section having first and second portions;

(b) arranging first, second and third field coils with the first being situated at said entrance section and the second and third being situated at said intermediate section;

(c) interposing first and second means for establishing an abrupt change in a magnetic field, said imposition placing said first means for establishing an electric field between said first and second field coils and said second means for establishing an abrupt change in a magnetic field between said second and third field coils, said first field coil and said first abrupt changing means comprising a first operating region, said second field coil and said first and second abrupt change means comprising a second operating region, and said third field coil and said second abrupt change means comprising a third operating region;

(d) adjusting the first field coil to supply the strength of an axial magnetic field corresponding to a first predetermined quantity f_1 in said first operating region;

(e) adjusting the second field coil to supply the strength of an axial magnetic field corresponding to a second predetermined quantity f_2 in said second operating region;

(f) adjusting the third field coil to supply the strength of an axial magnetic field corresponding to a third predetermined quantity f_3 in said third operating region;

(g) adjusting said f_1 and f_2 quantities to one of the following relationships: (1) $(f_1=f_2)$; (2) $(|f_1|=-|f_2|)$ and (3) $(f_1\neq f_2)$.

9. The method of using a gyrotron gun according to claim **8**, wherein said beam-forming is further determined by a third factor: (3) the spread of the axial velocity v_z of said beam and wherein said method further comprises the steps of:

(h) arranging a pair of bucking coils near said cathode; and

(i) adjusting the level of current in said bucking coils to control said spread of axial velocity of said beam.

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