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Friedlander

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[54] **HIGH ENERGY BEAM LAUNCHING APPARATUS AND METHOD**

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[52] **U.S. Cl.** **313/460;** 315/3.5; 315/39.3; 328/227; 328/233; 313/442
[51] **Int. Cl.** **H01j 29/00**
[58] **Field of Search**..................... 315/3.5, 3.6, 39.3; 328/227, 233; 313/82, 82 BF, 84

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Assistant Examiner—Saxfield Chatmon, Jr.
Attorney, Agent, or Firm—Stanley Z. Cole; D. R. Pressman; R. B. Nelson

[57] **ABSTRACT**

Apparatus and method are disclosed for launching a high energy beam of charged particles along an axis into a substantially long path region from an exit aperture, in a manner such that the beam remains confined without application of external focusing fields in the region. The apparatus comprises a cathode, which is a source of electrons to compose the beam, and electrode means for producing an axial accelerating electric field to accelerate electrons in the beam to a relativistic velocity in an accelerating space. At relativistic velocity, the beam itself produces a solenoid-shaped magnetic field which undesirably tends to converge the beam when ionized gas molecules neutralize the space charge in the beam. An external magnet means for producing an axial magnetic field in the accelerating space and a radial magnetic field at the exit aperture, imparts a cyclotron angular momentum to the electrons. The cyclotron angular momentum provides a force to the electrons to substantially cancel the force of the self-magnetic field. Once the beam leaves the accelerating and cyclotron motion inducing space, it remains confined to a desired range of cross section. Such beams may be used for heating plasmas, or in high power microwave oscillators and amplifiers.

7 Claims, 7 Drawing Figures

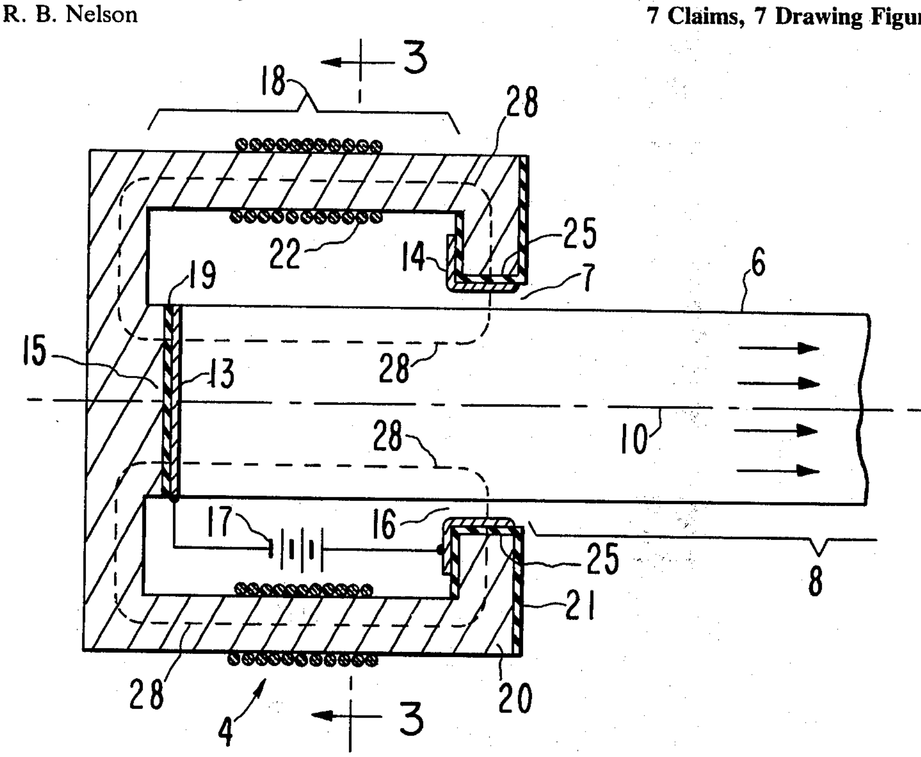


FIG. 1

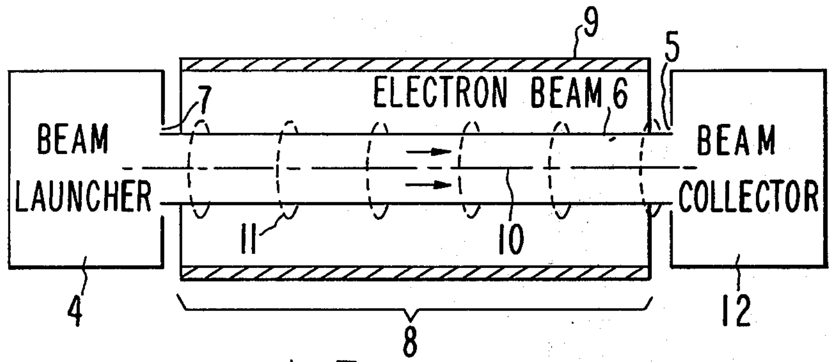


FIG. 2

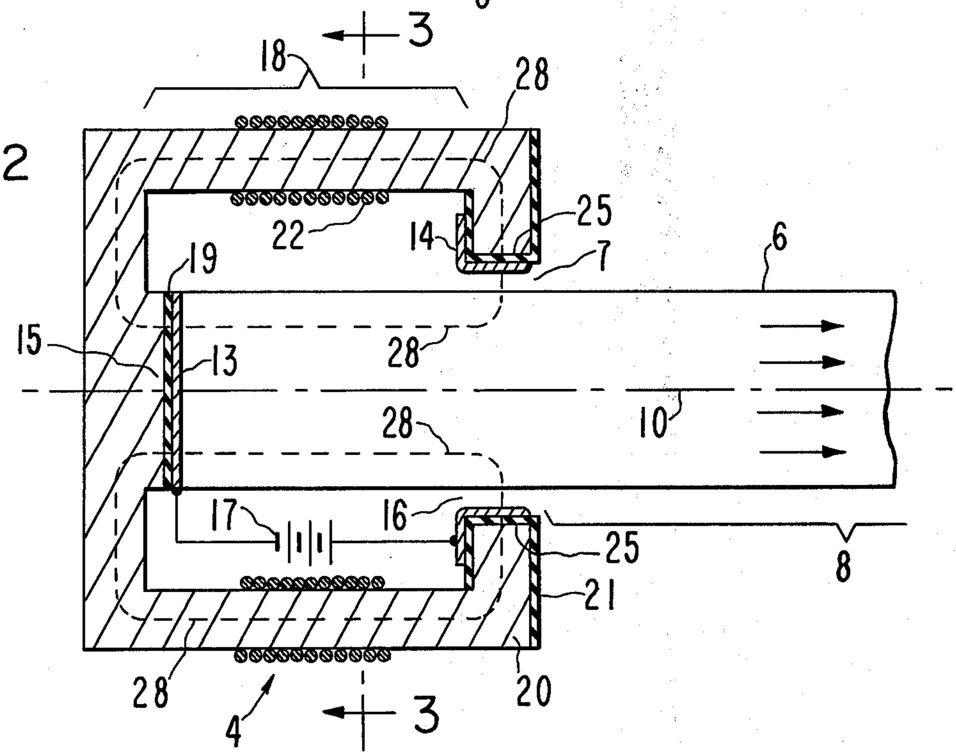


FIG. 3

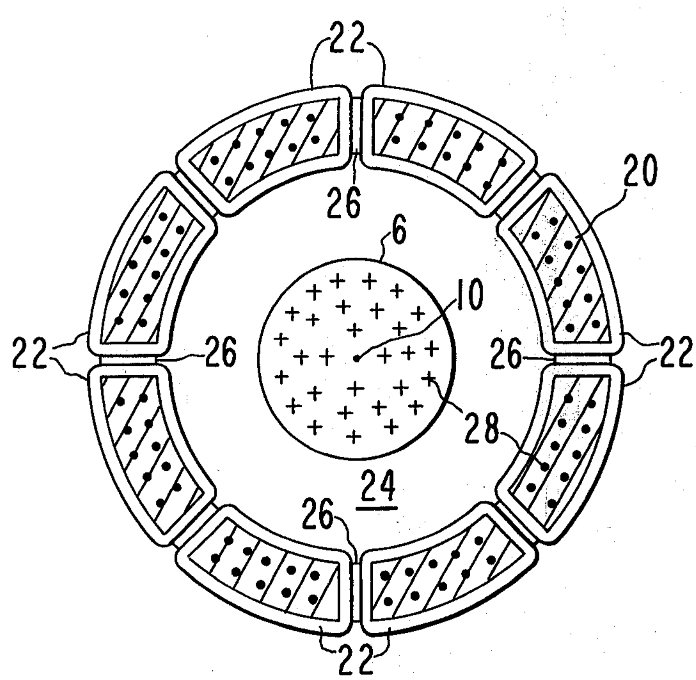


FIG.4

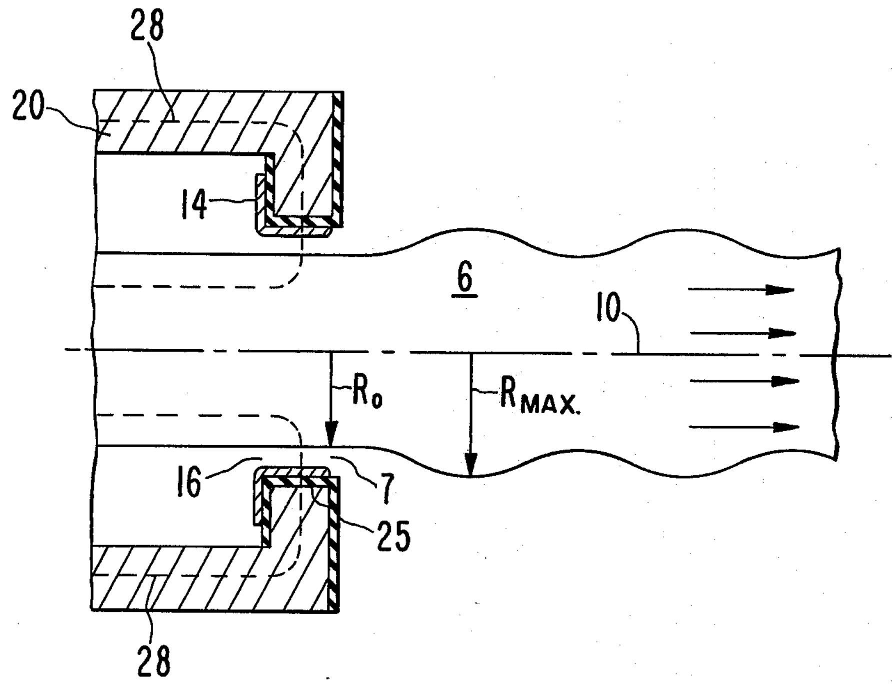


FIG.5

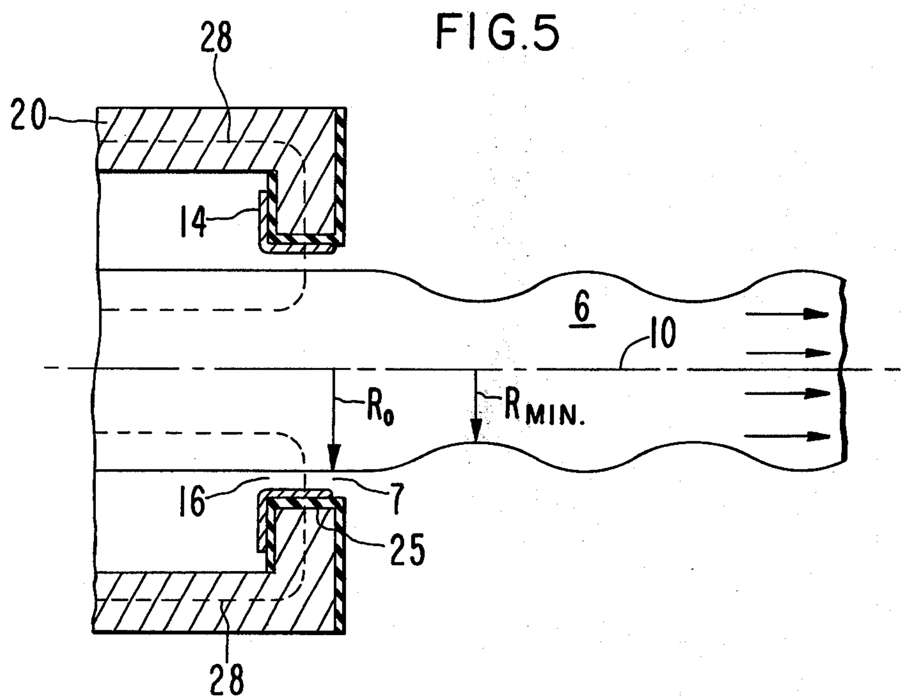


FIG. 6

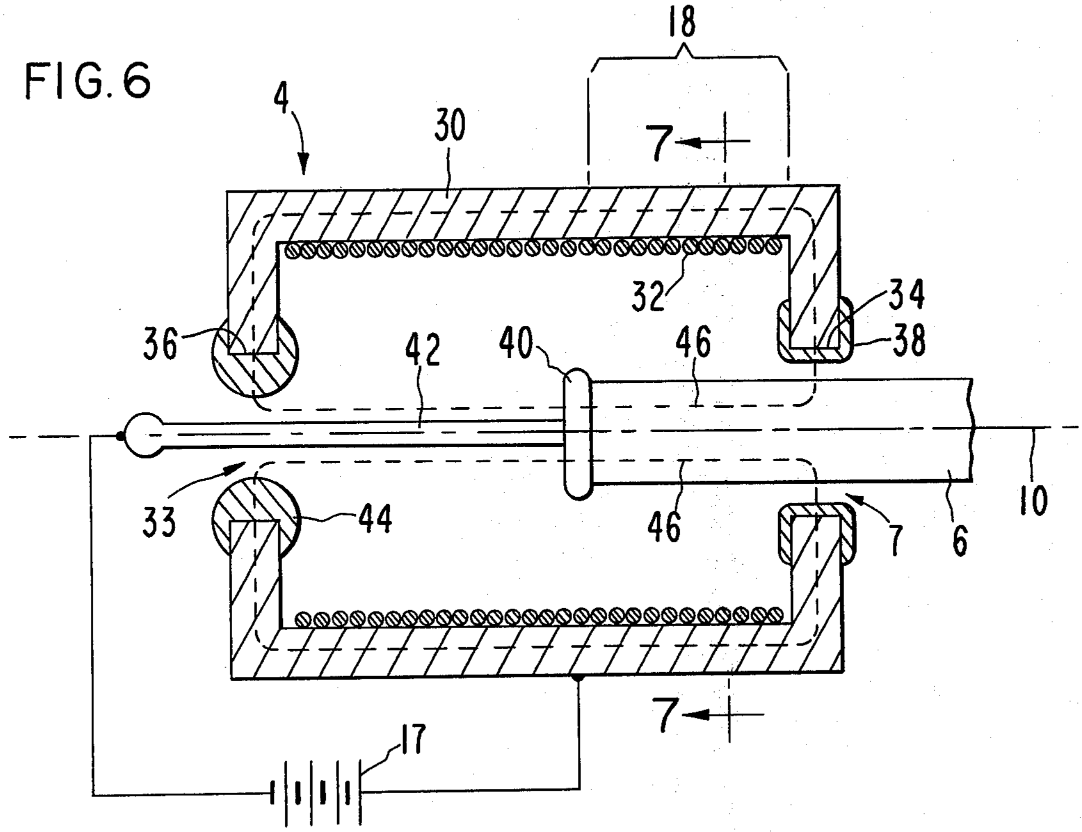
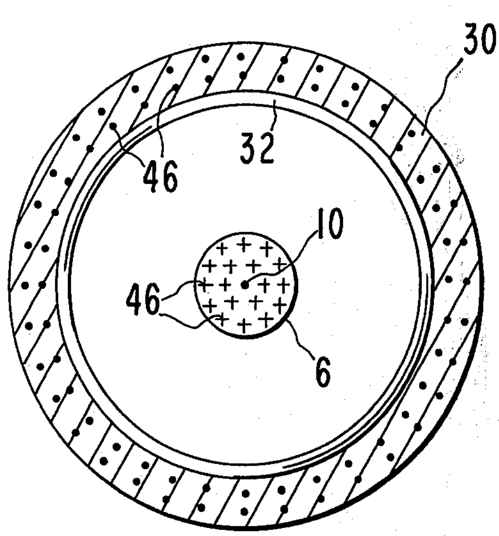


FIG. 7



HIGH ENERGY BEAM LAUNCHING APPARATUS AND METHOD

FIELD OF THE INVENTION

The present invention is generally related to the production of a beam of charged particles and is more particularly related to launching a beam of charged particles into a region under conditions where the beam remains confined or focused after it leaves a launching space without the application of external focusing fields in the region.

BACKGROUND OF THE INVENTION

If one could produce a high current beam of high energy charged particles which would remain confined in cross section while propagating down an axis over a relatively long path, without the necessity of applying external electric or magnetic fields to the beam over the long path, then such a beam would prove valuable as an implement for heating plasmas or as a high power beam for microwave amplifiers and oscillators such as travelling wave tubes, klystrons and magnetrons.

The requirement of high energy particles within the beam means that for a beam composed of electrons, these electrons would have to propagate at relativistic velocities, i.e., velocities significantly approaching the speed of light. In producing such a beam, superficially similar and yet significantly different problems arise than have occurred in the production of nonrelativistic beams.

It is well known that a beam of charged particles, in particular an electron beam, propagating in a vacuum system, can be produced by a suitable electron gun structure comprising a cathode source of electrons, accelerating electrodes and focusing electrodes. When it is desired to produce a laminar or substantially pure longitudinal electron flow in a high vacuum system, the concern is generally with divergence or broadening of the beam in response to a coulomb repulsive force between the electrons comprising the beam.

An electron beam is said to be ion-neutralized if positive ions are present which tend to electrically neutralize the electrons in the beam, thereby diminishing the beam diverging forces. These positive ions are produced generally through collisions between gas molecules and relatively high energy electrons. At the electron and gas pressures used in present devices, for example, microwave tubes, complete ion-neutralization is rarely if ever achieved (and usually not even attempted). It is generally therefore the prior art practice, where the beam is not completely ion-neutralized, to produce an axially aligned electron flow by providing an axial, external magnetic field over the entire beam path length, except for the collector region. Thereby, the beam is magnetically focused so that a cyclotron or spiraling motion of the electrons in a magnetic field is caused. In the prior art technique called confined flow, the external magnetic field should have an axial component at the cathode electron source and should be axial in the region beyond the accelerating electrode.

However, by using a second prior art technique known as Brillouin flow, it is possible for the electron beam to have an axial magnetic field over only the major portion of its path length generally at and beyond the accelerating electrode, and no axial component of magnetic field is allowed at the cathode location. Instead, there may be a radial magnetic field component or as is usually the case, no magnetic field at the cathode. It is still generally necessary in Brillouin flow, to have an axial magnetic field over all of the beam path (for which the beam is to remain focused), except for its inception at the cathode. When the beam goes from the region of radial field into the axial magnetic field, it is imparted with a uniform rotational velocity about its axis, i.e., cyclotron motion. If the magnetic field is chosen to be a particular value related to a quantity describing the electron beam, termed the plasma frequency, there is a balance between an outward radial force due to space charge repulsion and an inward radial centripetal acceleration due to the cyclotron or spiralling motion induced on the beam by the magnetic field which produces axially aligned or laminar flow.

At sufficiently high relativistic electron energies, above roughly one hundred thousand electron-volts, and with sufficiently poor vacuum, an electron beam can be substantially ion-neutralized due to the presence of neutralizing positive ions produced by the high energy electrons of the beam colliding with gas molecules, without suffering substantial energy loss due to scattering. Therefore, when the electrons of the beam are accelerated to such relativistic velocities in a sufficiently poor vacuum, there is a negligible beam diverging force due to space charge repulsion and superficially one might expect that such a beam could be easily propagated in a confined manner without the application of external fields. However, as the beam current and electron velocity are increased an essentially circumferential magnetic field, circling around the beam axis, and produced by the beam itself, becomes extremely significant. This magnetic field produced by all the electrons in the beam produces an inward radial force on each individual off-exact-center electron comprising the beam, whereby the beam has a tendency to converge, rather than diverge and produce an extremely high electron density at the beam axis. This beam convergence is undesirable because the neutralizing ion density gets correspondingly high and scatters electrons from the beam, whereby the beam would tend to lose electrons as it propagates. Thus, in order to produce a high current beam of high energy particles it is necessary to prevent such beams from collapsing due to the significant self-magnetic field.

SUMMARY OF THE INVENTION

A source, such as a cathode source of electrons, provides charged particles to a gun region having an exit aperture. In the gun region, an axial electric field is provided by an electrode and potential thereon, the electrode being axially spaced downstream from the cathode, whereby the electrons which comprise an electron beam are accelerated to relativistic velocity. Within a sufficiently poor vacuum environment, the relativistic beam is substantially ion-neutralized and produces a significant self-magnetic field which circles about the beam axis and would tend to undesirably converge the beam to a point where increased neutralizing ion density would scatter the electrons of the beam. To oppose this converging tendency, a magnet means provides an axial magnetic field throughout the gun region except at the exit aperture where the magnetic field has a radial component. As the electrons cut this radial magnetic field a cyclotron or spiralling particle motion is induced which causes a centrifugal (rather than centripetal) force substantially opposing the converging force due to the beam self-magnetic field. Upon exiting the gun region the beam remains substantially confined to a predetermined radius or range of radii without application of external fields thereto as a result of the continued spiralling motion due to conservation of angular momentum.

Viewed differently, the axial magnetic field within the gun region provides an initial angular momentum whereby the particles of the beam may follow, outside of the gun region, a substantially solenoidal or spiralling path. The spiralling path cuts the essentially circumferential lines of the self-magnetic field in a manner such that an inward radial force on the electrons due to cutting the field is substantially balanced by the centrifugal force of the electron angular momentum.

Brillouin flow, it will be recognized, is just the opposite of the invention. In the invention, a beam of charged particles traverses first an axial magnetic field, second a radial magnetic field and third a field-free region while in Brillouin flow the beam traverses these regions in the opposite order, i.e., first a region without magnetic field, second a region of radial magnetic field and third a region of axial magnetic field. In the case of both the invention and Brillouin flow, the beam is confined in cross section when it is in the third region, i.e., the field-free region in the invention and the axial magnetic field region in Brillouin flow.

OBJECTS OF THE INVENTION

It is an object of the present invention to provide a new and improved apparatus and method for launching a confined beam of relativistic charged particles.

It is a further object to provide a method and apparatus for propagating a relativistic charged particle beam that remains confined without application of external focusing fields thereto.

It is another object of the present invention to provide gun apparatus for launching a beam of charged particles from an exit aperture having an axial magnetic field producing means within the gun apparatus and radial magnetic field producing means at the exit aperture for inducing a circumferential component of motion of the particles to substantially oppose a beam converging force due to a self-magnetic field produced by the beam.

It is an additional object of the present invention to provide gun apparatus for a beam of electrons having an electrode means within the gun for accelerating the electrons to relativistic velocity and a magnet means within the gun for producing a magnetic field of proper strength and orientation that the electron beam remains confined in cross section over a relatively long path length after leaving said gun apparatus.

It is a further object of the present invention to provide a new and improved method of and apparatus for launching a confined beam of charged particles wherein the particles are accelerated to relativistic velocity and are rotated at a predetermined rate within a launch region.

The above and still further objects, features and advantages of the present invention will become apparent upon consideration of the following detailed description of two specific embodiments thereof, especially when taken in conjunction with the accompanying drawing.

BRIEF DESCRIPTION OF THE DRAWING

FIG. **1** is a schematic of the power transmission system of the invention having a beam launcher for launching an appropriately confined high energy electron beam over a substantial path length and a beam collector at the end of the path length for collecting the energy from the beam.

FIG. **2** is a cross-sectional view of the beam launcher of FIG. **1.** A laminar beam produced by ideal launch conditions is shown.

FIG. **3** is a cross-sectional view of FIG. **2** along the lines **3—3.**

FIGS. **4** and **5** are views similar to FIG. **2** showing tolerable shapes of the beam in FIG. **2** under non-ideal launch conditions.

FIG. **6** is a cross-sectional view of an alternate embodiment of the beam launcher of FIG. **1.**

FIG. **7** is a cross-sectional view of FIG. **6** along the lines **7—7.**

DETAILED DESCRIPTION OF THE INVENTION

Referring first to FIG. **1,** there is shown a charged particle beam launcher, electron gun **4** which launches at relativistic velocity a confined ion-neutralized electron beam **6** through aperture **7** along axis **10** into a "field-free" region **8** enclosed by conduit **9.** By a field-free region is meant a region where no external electric or magnetic fields exist ideally. The conduit enclosing this region has a vacuum on the order of 10^{-3} to 10^{-7} torr to provide neutralizing ions, preferably of low scattering cross section such as Helium. Small fields such as the earth's magnetic field either do not markedly affect the electron beam **6,** or, depending on the path length, current density and beam velocity, must be compensated for, or shielded from the beam by making the conduit **9** which coaxially surrounds the beam of a high magnetic permeability, high electric conductivity material. Facing gun **4** at the end of field-free region **8** is a collecting or receiving apparatus **12** having an aperture **5** for collecting the beam. Ideally, the electrons arrive at receiving apparatus **12** at their launch velocity, corresponding to an electrical potential. Also, ideally all the electrons launched arrive, and at a rate corresponding to an electrical current. The product of the electrical potential and the current is electric power suitable for doing useful work. In microwave amplifier and oscillator applications, the beam is interacted with microwave energy (not shown) along a portion of its path. The beam in that case loses a significant portion of its energy to microwave amplification prior to the arrival of the beam at the collecting apparatus **12.**

To transfer extremely high power from gun **4** to the collector apparatus **12,** or to microwave energy, it is necessary for the electron beam to be of both high current and velocity. In fact, the beam velocity is so high that the electrons are considered as highly relativistic as they would be travelling close to the speed of light. For example, providing to the beam electrons kinetic energies in excess of one hundred thousand electron volts gives a beam velocity of within 46% of the velocity of light. At these velocities the beam is ion-neutralized by the provision of the poor vacuum in conduit **9** and a significant magnetic field is produced by the beam itself. The magnetic field includes lines **11** having an essentially circular shape. Lines **11** circle about the beam longitudinal axis to produce an undersirable beam converging force. The corresponding neutralizing ion density has a tendency to become so great as to scatter the beam electrons, and prevent many of them from reaching the beam collector. Thus, it is desired for the beam to neither converge nor diverge, but rather be confined to a predetermined cross section or range of cross sections. The launcher 4 must pre-compensate for the beam's self-magnetic field to allow the electron beam to be so confined without providing a force on the beam downstream of the launcher.

FIG. 2 shows, in greater detail, the beam launcher or gun 4 for launching the confined electron beam 6 at relativistic velocity. The launcher 4 has a planar cathode 13 perpendicular to the beam axis 10. Spaced downstream from the cathode 13 and coaxial with the axis 10 is an annular accelerating electrode 14 having an aperture 16 through which the accelerated electrons of the beam pass. Aperture 16 immediately precedes and is coaxial with the aperture 7 of the gun 4. To accelerate electrons from the cathode 13 to a relativistic velocity, the electrode 14 is positively d.c. biased with respect to cathode 13 by a suitably high voltage in excess of one hundred thousand volts by power supply 17 (which would actually be located outside of gun 4). The cathode and accelerating electrode are respectively insulated from a magnetic core 20 by insulating layers or gaps 19 and 21.

As the electrons are accelerated in the space 18 between the cathode 13 and the accelerating electrode 14, and begin to achieve relativistic velocity, the beam develops a large self-magnetic field that has a tendency to undesirably converge the beam and would continue to do so in the long path 8 into which it is launched through aperture 7. To avoid this beam convergence, a magnet means of a predetermined strength is provided to produce a substantially constant axial magnetic field within the space 18. The axial field in space 18 focuses the beam within the space into axially moving relativistic electrons. At the exit aperture 7, the axial magnetic field ends, and, because of the nature of magnetic flux lines, becomes a radial magnetic field. This radial magnetic field at the exit aperture 7, as it is cut by the axially moving electrons of the beam, produces a uniform rotation rate of electrons about the beam axis. Thus, the electrons of the beam, after leaving the exit aperture, have a spiralling motion about the beam axis due to conservation of their angular momentum, with an associated centrifugal force for substantially opposing the beam converging force of the self-magnetic field. The strength of the magnet means may be chosen to produce a centrifugal force exactly cancelling the self-magnetic field force thereby producing in the long path 8 a laminar beam of constant cross section. In practice however, it is sufficient to use a launcher magnetic field strength which confines the beam to a suitable range of cross sections in the long path 8 as is discussed infra with respect to FIGS. 3, 4 and 5.

The axial and radial magnetic fields which the electron beam encounters in seriatim within the launcher 4 are produced by a d.c. electromagnet means comprising a low reluctance core 20 in combination with a coil formed of windings 22 excited by a d.c. source (not shown). The core, as can be seen from FIG. 3, has an annular cross section with a relatively large aperture 24 coaxial with the electron beam axis 10 in the accelerating space 18. Behind the cathode 13, the core 20 is solid, forming a circular pole piece 15, coaxial with the cathode. At the location of the accelerating electrode 14, the core 20 is annular in shape and turns radially inward to a smaller aperture forming a cylindrical surface 25 which is a pole piece that surrounds the electron beam at the gun aperture 7. The core 20 has radial and axial slots 26 for sectoral current windings 22, each of which has an axis parallel to the electron beam axis. The d.c. current supplied to windings 22 produces d.c. axial magnetic flux lines 28 directed within the sector of the core 20 enclosed by the winding. The flux lines 28 traverse a path that extends radially inward from each sector through the solid pole piece behind the cathode, thence perpendicularly through the cathode, and axially along the electron beam over the accelerating space 18, and is completed by turning radially outward through the cylindrical pole piece 25 to produce the radial magnetic field at the exit aperture.

Since the core is a low reluctance path, substantially all of the magnetomotive force therein produces the radial magnetic field at the exit aperture 7 and an axial magnetic field in the accelerating space 18, within the electron launcher 4, along the electron beam. It should be understood that a permanent magnet shaped like the core and magnetized to produce the flux lines 28 is also suitable.

FIGS. 6 and 7 show an alternate embodiment of the beam launcher 4 including an outer low reluctance cylindrical core 30 surrounding an inner solenoid winding 32. The core 30 and solenoid winding 32 are coaxial with the beam axis 10. Core 30 is annular in shape and turns radially inward at its front and back ends to two smaller apertures 7 and 33 respectively forming front and back cylindrical pole pieces 34 and 36. Lining front cylindrical pole piece 34 is an annular accelerating electrode 38, through which the launched electron beam 6 passes. A generally planar cathode 40 is located on axis 10 intermediate the front and back magnetic pole pieces 34 and 36 and facing the front aperture 7. A thin conductive stem 42 supports the cathode 40 from the back and protrudes through the core's back aperture 33. Power supply 17 supplies accelerating potential between the core 30 and the cathode 40 via its stem 42 causing an axial accelerating electrical field between the cathode 40 and the accelerating electrode 38. Core 30 is preferably grounded. Lining the back pole piece 36 is an annular smooth corona ring 44 for inhibiting arcing between the core's back aperture 33 and the stem 42.

When the solenoid winding 32 is supplied with current, magnetic lines 46 are produced which traverse a path that extends axially along axis 10, radially outward through the front annular magnetic pole piece 34 to produce the radial magnetic field at the exit aperture 7, axially along the core and radially inward through the back annular pole piece 36. Thus, because of the intermediate location of cathode 40 within the core 30, an axial magnetic field exists between the cathode and the launcher's exit aperture 7, while a radial magnetic field exists at aperture 7.

The axial magnetic field over the space 18 provides a focusing action and the radial magnetic field at the exit aperture 7 produces a cyclotron motion of the electrons comprising the beam to produce a centrifugal force to substantially balance the beam converging force of the self-magnetic field. The spin is produced by cutting the radial magnetic field lines in the region where the beam is launched. The spin, as taught by Busch's Theorem, depends only on the difference between the magnetic flux enclosed by imaginary circles coaxial with the beam axis. These imaginary circles are located at a pair of parallel planes along the beam axis. Since the electrons exit into a field-free region, the resultant electron spin depends only on the magnetic flux passing through a plane in the gun structure, such as the cathode. Busch's Theorem may then be written for this situation as:

$$\omega = \frac{e}{m} \frac{B}{2} \frac{r_p 2}{r^2} \qquad (1)$$

where:

ω = electron spin angular velocity upon exiting the gun,
e = charge of electron,
m = mass of electron (modified to include the relativistic effect),
r = radius of particle from beam axis after exiting gun,
r_p = radius of particle at a plane within the gun, and
B = magnetic flux density at the plane.

For a particular value of ω, there is a corresponding centrifugal force of:

$$\left(\frac{e}{m}\right)^2 \frac{B^2}{4} \frac{r_p 4}{r^3} \qquad (2)$$

The inwardly directed force due to the self-magnetic field at particle radius, r, is given by:

$$\frac{\rho \mu_o r e v}{2} \qquad (3)$$

where:

ρ = current density within the beam,
μ_o = magnetic permeability of free space, and
v = electron velocity

For the inward force and centrifugal force to cancel, the optimum flux density at the cathode is as follows:

$$B_o = \left(\frac{r}{r_p}\right)^2 \sqrt{2\frac{m}{e}\mu_o \rho v} \qquad (4)$$

It is then apparent that electrons at all radii in the beam are focused by the same conditions allowing laminar flow. If the radius of each electron in the beam is set equal to the radius at which it left the cathode a pure laminar flow would result within as well as outside the gun structure, with the simplifying assumption that the electrons of the beam had already reached their final velocity just at the cathode. Because the electrons are not yet fully accelerated until they reach the accelerating electrode (**14** in FIG. **2**, **38** in FIG. **6**) just prior to reaching the radial magnetic field, Equation (4) is most applicable to relate the radius of an electron at electrode **14** (or **38**) to its radius in the long path **8**.

Reference is now made to FIGS. **4** and **5** which show the launched beam **6** when the magnetic flux density within the launcher is different from the optimum value previously derived. With non-optimum magnetic field, a scalloping or standing wave pattern of the envelope of the beam is produced outside of the exit aperture **7** rather than the absolutely straight, laminar beam produced with optimum magnetic field.

FIG. **4** shows the shape of the launched beam with a magnetic flux density within the launcher being greater than optimum. The beam cross section periodically bulges to a maximum radius R_{Max} and periodically pinches to the radius R_o at which it is launched at the exit aperture **7**. Periodic bulging is due to an excess of diverging centrifugal force over converging self-magnetic field force. The electrons of the beam diverge after they leave the launcher exit aperture **7** because of this diverging force. But, as the electrons diverge, the centrifugal force decreases because of increased radius and decreased spin rate until the beam converging force dominates and accelerates the electrons radially inward. A point is reached where the centrifugal force dominates and again propels the electrons radially outward. Since the forces at work are conservative, a periodic bulging and returning to the launch radius is produced over the entire long path **8**.

Referring to FIG. **5**, with the magnetic flux density within the launcher less than optimum, the beam periodically pinches to a minimum radius because of an excess beam converging force and periodically returns to the launch radius R_o. Upon considering the equations of motion of the electrons of the beam outside the exit aperture by well known differential equation techniques and setting the electron radial velocity to zero, minimum and maximum radii of the standing wave envelope of the beam can be found according to the following normalized equation where a minimum radius exists for flux densities less than optimum while a maximum radius exists for flux densities greater than optimum:

$$\frac{B}{B_o} = \sqrt{\frac{\ln \left(\frac{R_o}{R}\right)^2}{\left(\frac{R_o}{R}\right)^2 - 1}}$$

where:

B is the actual flux density within the launcher,
B_o is the optimum flux density,
R_o is the launch radius of the beam, and
R is the maximum or minimum radius of the beam scalloping, depending on whether this radius is greater than or less than R_o, respectively.

To summarize, if the applied flux density is stronger than optimum, the beam over the long path **8** would periodically bulge to radius R_{Max} and periodically return to the radius at which it was launched as shown in FIG. **4**. On the other hand if the applied flux density is less than optimum, the beam periodically pinches to radius R_{Min} and periodically returns to the launch radius as shown in FIG. **5**. Note that for $R = R_o$, the flux density is equal to the optimum value.

As should be apparent a certain degree of scalloping is tolerable for many applications. For example, a deviation on the order of 20% of an R_{Max} or an R_{Min} from the launch radius is tolerable for microwave tube applications.

While there have been described and illustrated two specific embodiments of the invention, it will be clear that variations in the details of the embodiments specifically illustrated and described may be made without departing from the true spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. An apparatus for launching a linear beam, having an axis, into a region substantially free from fields other than those produced by said beam and maintaining said beam focused in said region comprising:

A source of charged particles;

means for accelerating said charged particles to a relativistic velocity, whereby a self-magnetic beam-converging force exists;

means for providing a circumferential component of motion to said particles whereby centrifugal force on said particles opposes said self-magnetic force; and

an aperture means downstream from said accelerating means

whereby said beam remains limited in outward and inward excursions over a substantial path length after exiting said aperture without external forces applied thereto.

2. The apparatus of claim 1 where said circumferential motion causing means is means for producing a magnetic field penetrating said source and having a radial component threading said beam downstream of said source.

3. The apparatus of claim 2 where said particles are electrons and where said source is a cathode, where said accelerating means is an electrode and where there are additional means for biasing the electrode in excess of one hundred thousand volts positive with respect to said cathode.

4. The apparatus of claim 3 wherein the said electrode has an aperture for passing the electrons of the beam and where said electrode and said aperture means are coaxial with the beam axis.

5. The apparatus of claim 4 where said magnetic means comprises an annular pole piece coaxial with the beam axis and located substantially at said aperture means and a pole piece behind said cathode and coaxial with it.

6. The apparatus of claim 1 where said magnetic means comprises an annular pole piece coaxial with the beam axis and located at said aperture means and a pole piece behind said source and coaxial with it for producing an axial magnetic field which ends at said aperture means.

7. The method of launching a confined beam of charged particles down an axis into a substantially field-free region comprising:

accelerating charged particles from a source in an axial direction to a relativistic velocity whereby axially moving particles having a self-magnetic beam converging force are produced;

inducing a circumferential component of motion to the axially moving particles whereby a centrifugal force on said particles opposes said self-magnetic force dependent on their axial velocity;

shielding the particles of the beam from all further downstream external fields.

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