July 27, 1965 R. C. WINGERSON 3,197,680

CHARGED PARTICLE ANGULAR MOMENTUM CHANGER

Filed March 13, 1962 2 Sheets-Sheet 1

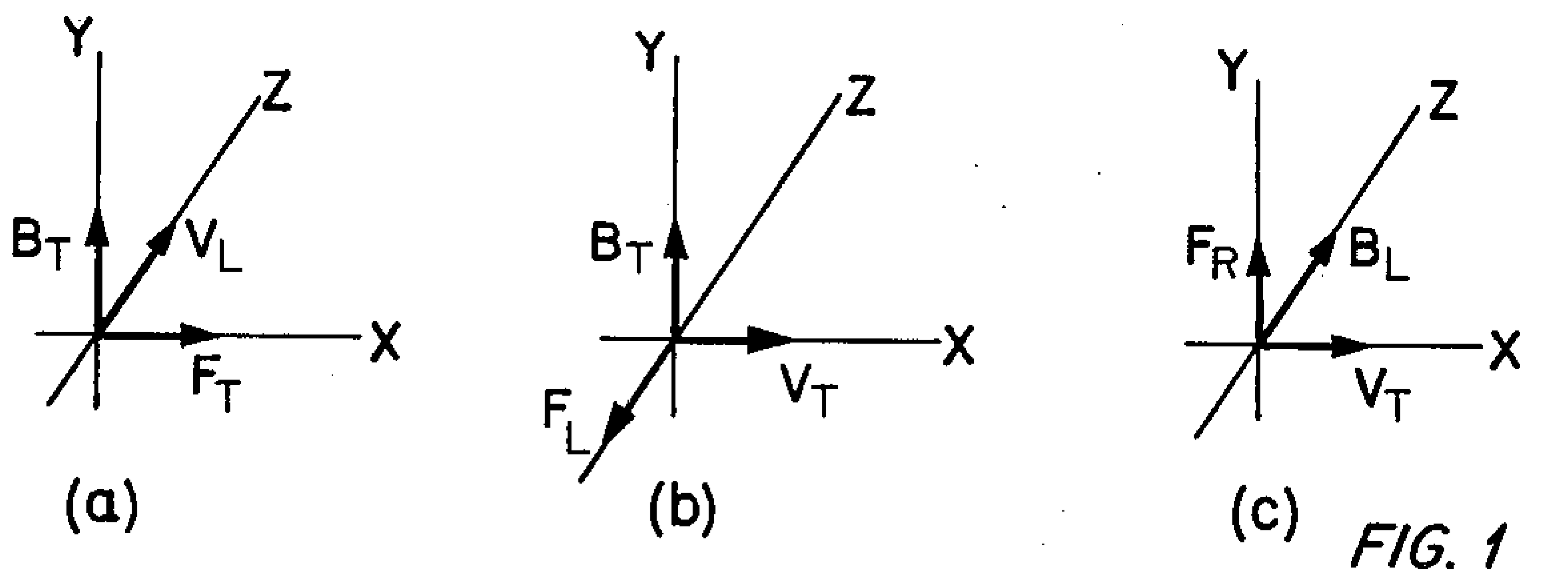

FIG. 1

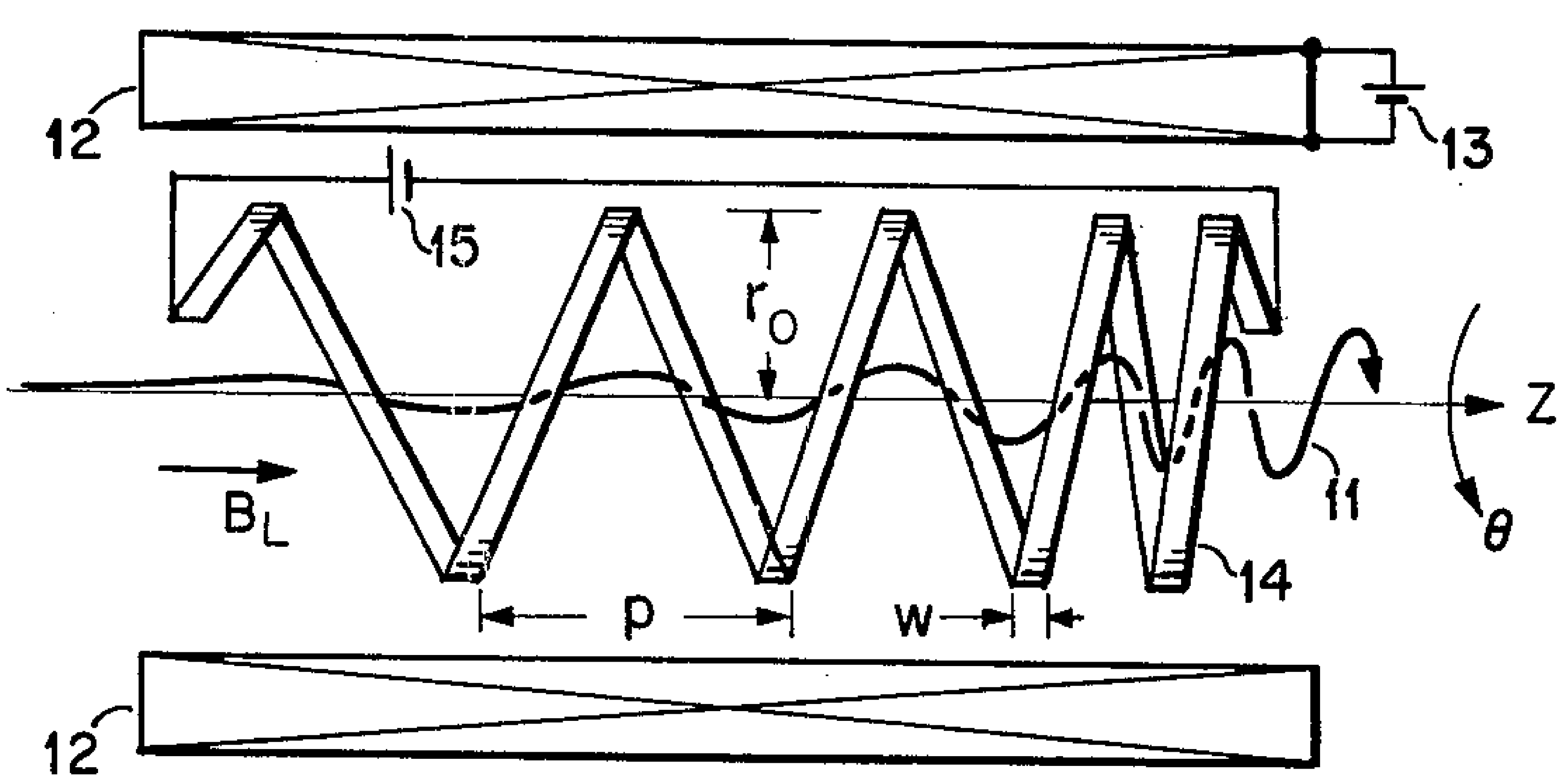

FIG. 2

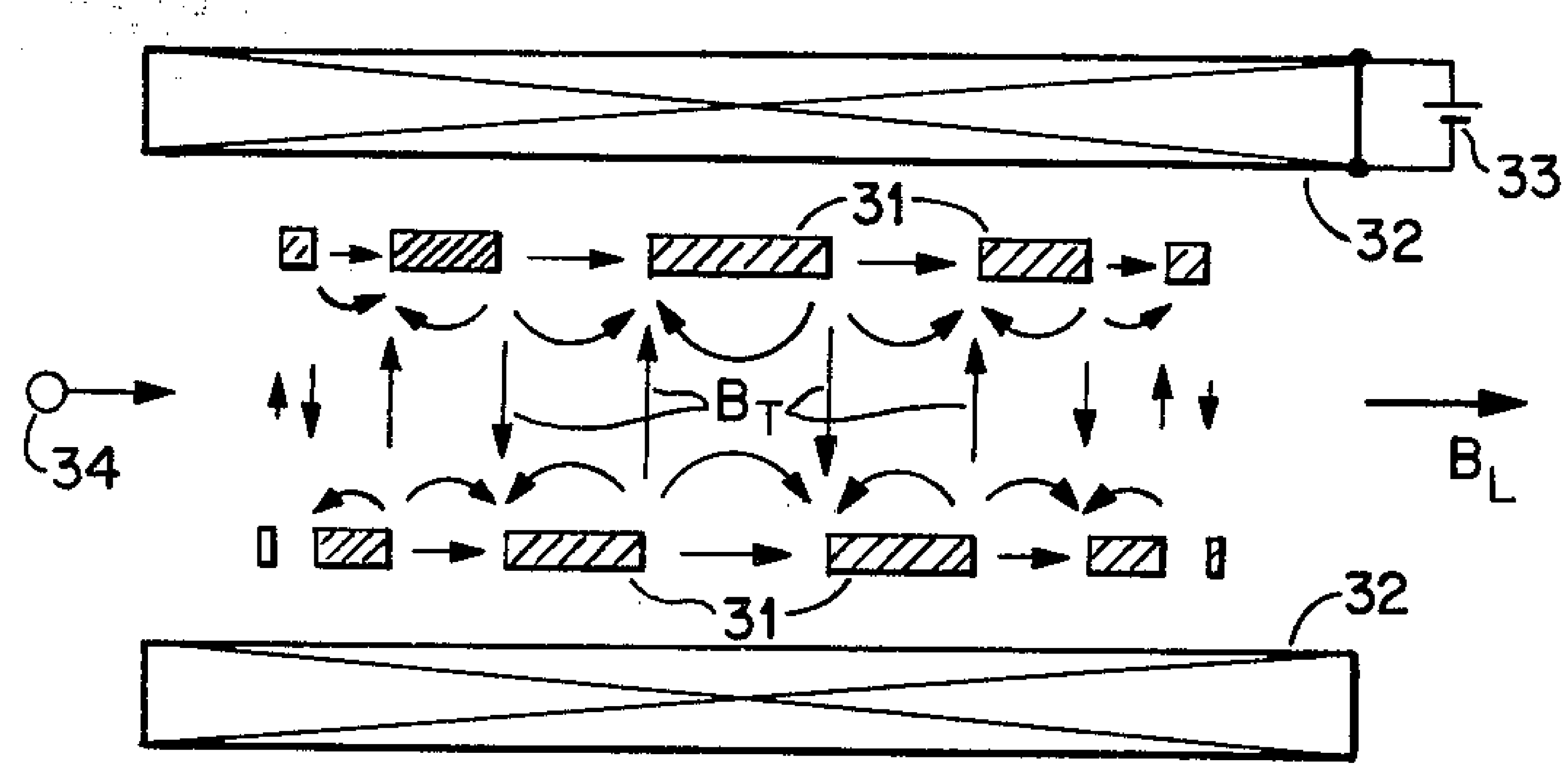

FIG. 3

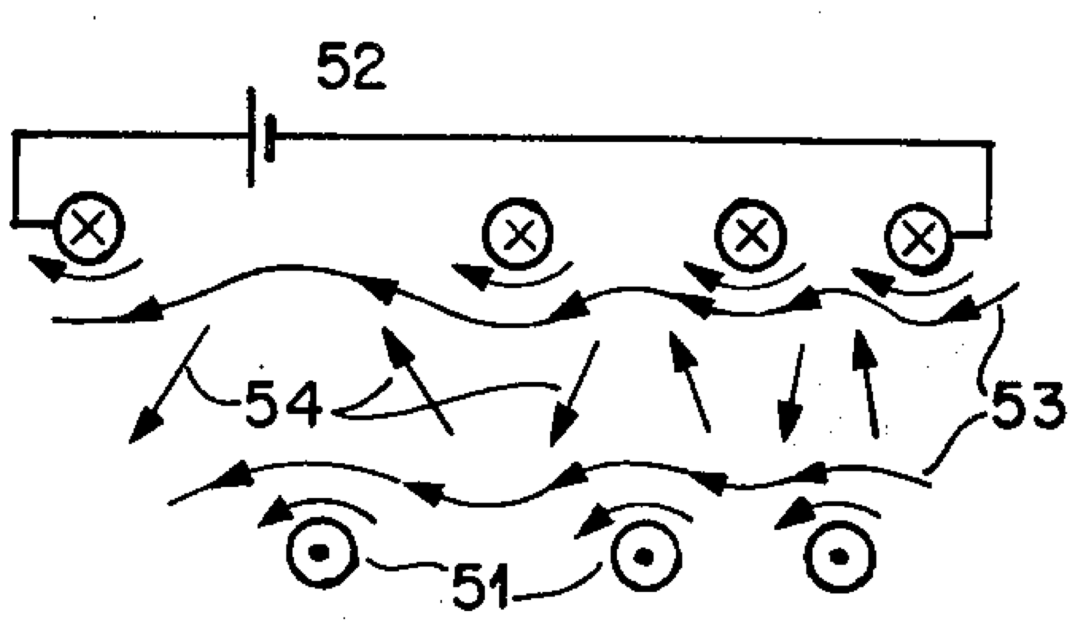

FIG. 5

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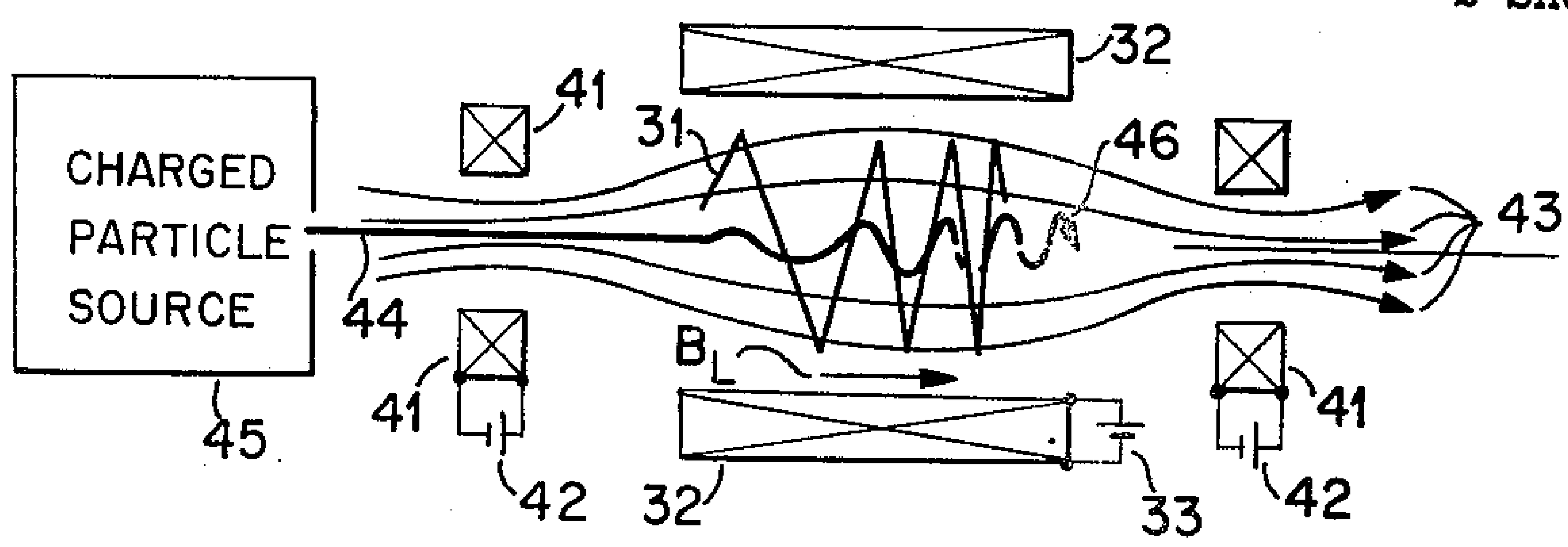

FIG. 4

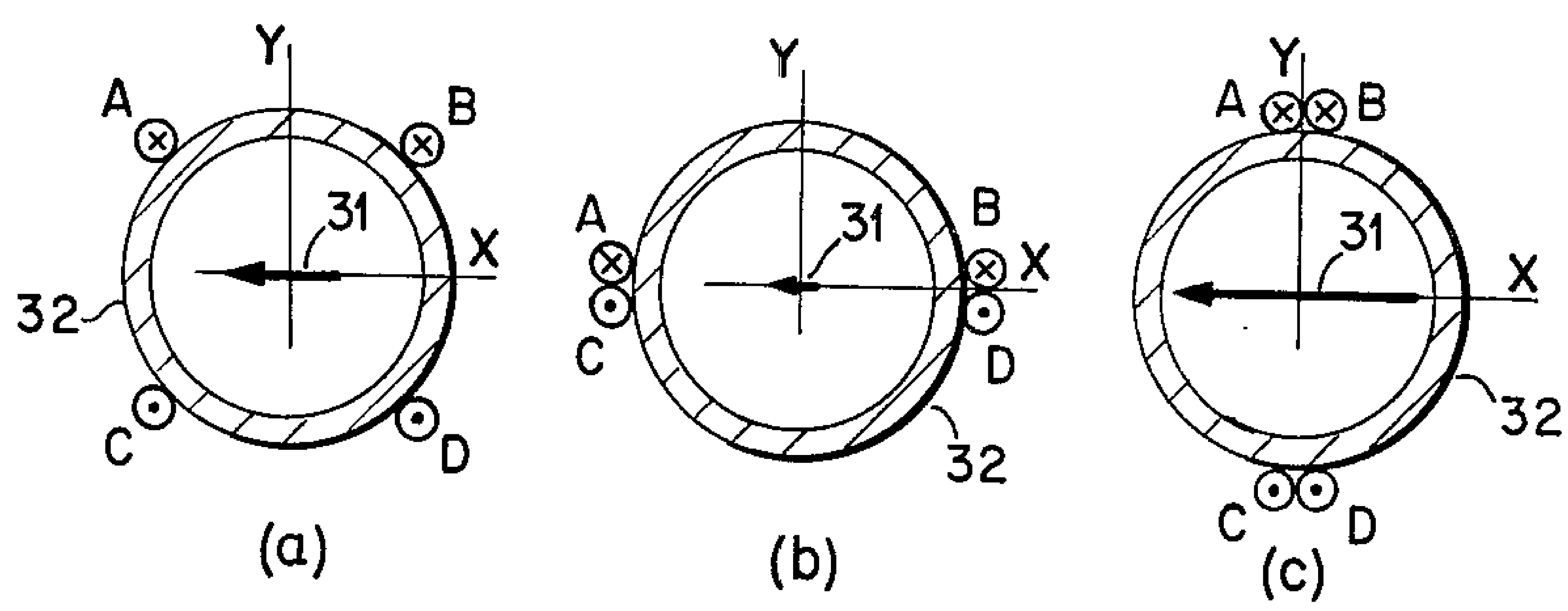

FIG. 6

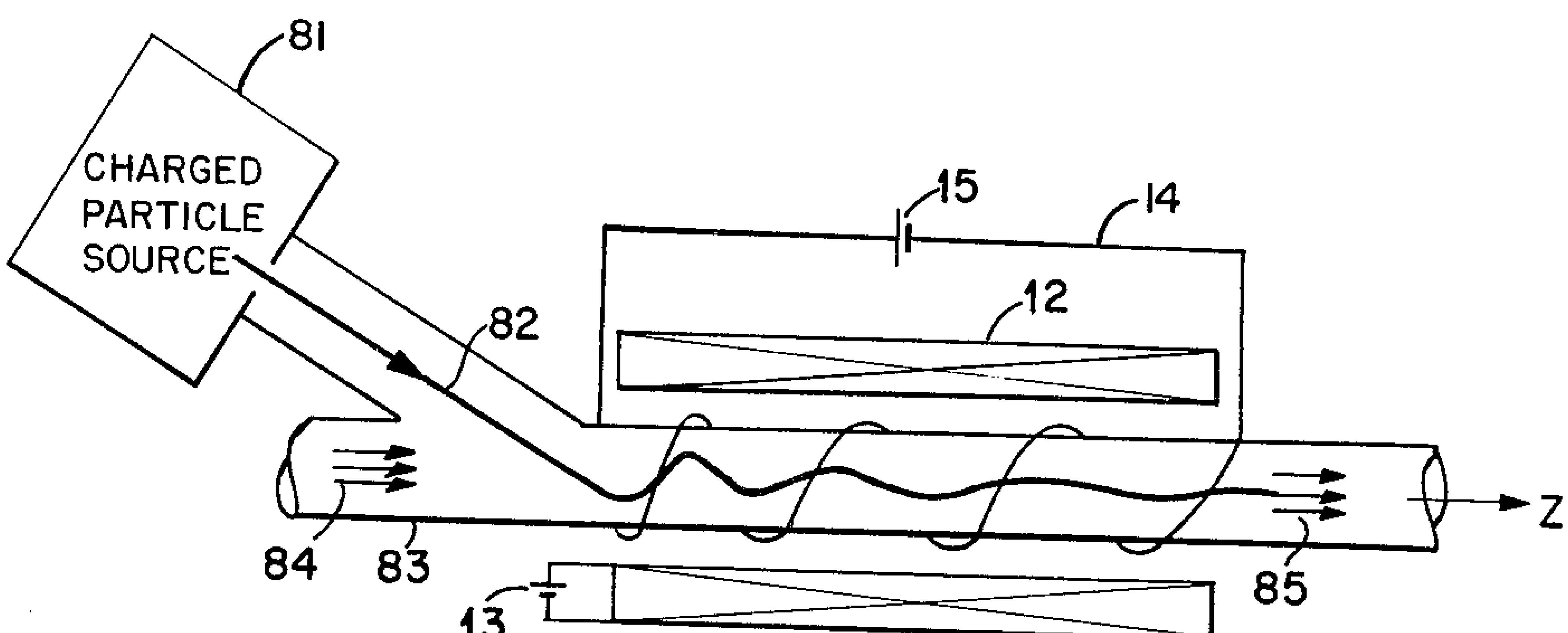

FIG. 8

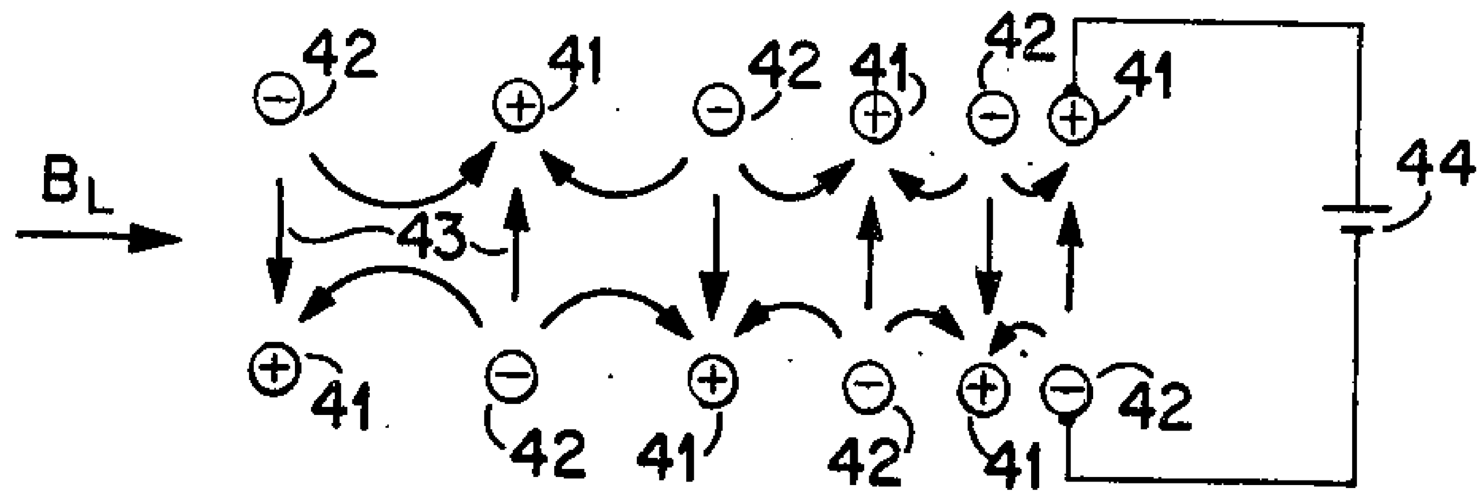

FIG. 7

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CHARGED PARTICLE ANGULAR MOMENTUM CHANGER

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13 Claims. (Cl. 317—200)

This invention relates to a method and apparatus for changing the angular momentum of a charged particle. More particularly, to means for changing the proportion of the energy of a charged particle between energy components parallel to and perpendicular to an almost uniform magnetic field without necessarily changing the total energy of the particle or the average strength of the field.

It is an axiom of physics that a charged particle injected into any static magnetic field configuraton will not be trapped, unless its energy is changed while it is within the field. As a result of this principle, ions injected from an ion source into a static magnetic field do not remain in the magnetic field for a time as long as might be desired. This situation exists with present methods for introducing ions into a thermonuclear device such as a magnetic mirror. There is great difficulty in introducing ions into the active region of the magnetic mirror in such a way that the ions are retained in the active region for a time period great enough to permit the ionic collisions to cause substantial numbers of fusion reactions. Also, other devices such as the synchrotron require that the electron or charged particle be introduced on a path as near as possible approximating the orbit of the charged particles already being energized by the synchrotron. This introduction of charged particles is a difficult problem and is achieved presently only at the expense of complex and intricate apparatus.

It is, therefore, a primary object of this invention to provide a device which will change the orbit of a charged particle by a unique magnetic or electric field configuration.

It is possible to change the energy components of a charged particle by means of a magnetic field of nonuniform intensity. The energy components referred to are those in the axial direction and the angular momentum component around the axis. A magnetic mirror accomplishes this interchange of energy components by developing a radial component of flux density at all regions within the mirror. Another technique for interchanging energy components by developing a radial component of flux density is described in J. Tech. Phys. U.S.S.R. 30, 249 (1960) [translation: Soviet Phys-Tech Phys. 5, 229 (1960)] where axially spaced coils produce a variable density axial field having a radial field component which varies in intensity and direction along the axis of the coils. Both of these devices are bilateral devices in that they do not discriminate in their effect on particles regardless of the axial direction of the particle velocity. Also, in the case of the magnetic mirror, at least, magnetic moment is constant. Magnetic moment is defined as $\frac{1}{2}mV_T^2/B_L$ where m is the mass of the charged particle, V_T is the velocity component of the charged particle transverse to the magnetic field intensity B_L.

These devices are to be distinguished from the device of the present application which is highly unidirectional in the sense that the device is effective in causing substantial change of longitudinal and transverse velocities of a charged particle when the particle is travelling in one direction whereas it will produce only minor perturbation on the particle when travelling in the opposite direction.

It is, therefore, another object of this invention to provide a device which is unidirectional in its effect upon the motion of a charged particle.

A particle having a trajectory in a static magnetic field and having energy components in a direction perpendicular to and parallel to the magnetic field has a property called adiabaticity wherein the magnetic moment of the particle tends to remain constant. This adiabaticity is often exploited in controlling particle motion. However, it is sometimes desired that the magnetic moment be changed. At present, this is extremely difficult to accomplish. It is possible to either increase or decrease particle magnetic moment in a controlled way by means of the device of this invention.

It is still another property of this device that the magnetic moment of the charged particle can be changed without changing its total energy.

These and other objects and advantages will become apparent from a consideration of the following specification and drawings, wherein:

FIGURE 1 is a diagram showing the forces exerted on a moving charged particle in a magnetic field.

FIGURE 2 shows a schematic diagram of a coil of variable pitch showing the trajectory of a resonant charged particle as its magnetic moment changes.

FIGURE 3 is a cross-sectional view of a variable pitch coil of ferromagnetic material showing the transverse field perturbation.

FIGURE 4 shows the coil of FIGURE 3 used in conjunction with a magnetic mirror.

FIGURE 5 is a cross-sectional view of a current-carrying coil of variable pitch showing the magnetic field pattern.

FIGURE 6 is an axially transverse cross-section of a quadrafile coil showing the field pattern.

FIGURE 7 is an electrostatic bifilar coil.

FIGURE 8 shows the coil of FIGURE 2 used in conjunction with a section of a particle accelerator.

In order to understand the principles of operation of the invention, the fundamental force equation on a moving particle of mass m and charge q and how this equation is applied in the invention is considered. In FIGURE 1*a*, a particle of positive charge q having a velocity V_L along the Z axis is subjected to a transverse force F_T along the X axis by the influence of the transverse magnetic field B_T along the Y axis, $F_T=qV_LB_T$. FIGURE 1*b* shows the resulting component of velocity V_T of the particle in the direction of force F_T. Velocity V_T of the charged particle causes a force F_L to be exerted upon the particle because of the effect of transverse field B_T. The force F_L is exerted along the axis Z in a direction to cause the particle to slow down from its original velocity V_L. The transverse velocity V_T also causes a force F_R of FIGURE 1*c* to be exerted on the particle because of the influence of the longitudinal field B_L. This force F_R is radially directed so that it will cause the particle to have a radial acceleration which causes the particle to assume a trajectory of circular cross section. Thus, it is seen that because of the transverse field B_T the particle has had its longitudinal velocity V_L decreased, has acquired a transverse velocity V_T and has been constrained by the longitudinal field B_L to follow a circular orbit. If B_L and B_T were of indefinite extent, the particle would follow a spiral trajectory which would have its longitudinal axis in the direction of the vector sum of B_L and B_T, and would have a circular path about this axis of constant radius r and of constant pitch p along this axis.

If it is desired to change the pitch without changing the energy of the particle, it is necessary to cause the particle energy in the longitudinal direction $\frac{1}{2}mV_L^2$, to be transferred in part to energy in the transverse direction, $\frac{1}{2}mV_T^2$. Since B_T reacting with V_T produces a force F_L opposing the velocity V_L, a device which will cause B_T to be continuously transverse to V_T is desired. since V_T will continuously change direction under the influence of B_L, a transverse magnetic field B_T which changes direction in unison with the transverse velocity V_T, will result in a condition where B_T and V_T are continuously at right angles—a condition which will produce maximum force F_L (and change in velocity V_L). Since the energy of the particle remains constant, a decrease in V_L must be accompanied by an increase in V_T. Thus the pitch ($p=2\pi m V_L/B_L q$) of the spiral trajectory of the particle decreases and the radius ($r=mV_T/B_L q$) of the cross section of the trajectory increases. Since B_T is rotating in direction as the particle proceeds in a direction along the Z axis, the longitudinal axis of the particle trajectory is along the Z axis rather than off the axis as in the case where B_T is only in the Y axis direction.

It is seen that a charged particle can be made to transfer energy from one component of velocity to another component of velocity transverse thereto by a magnetic field which is transverse to both velocity components and a second magnetic field in parallel with the component of velocity which is not changing direction. Whether the transfer is from the energy in the longitudinal velocity component V_L to energy in the transverse velocity component V_T or conversely depends upon the direction of the longitudinal field B_L, the charge on the particle.

This invention is concerned principally with devices for achieving energy transfer between longitudinal and transverse velocity energy components by providing a transverse magnetic field which is twisted so that the transverse field is always perpendicular to the transverse component of velocity of a charged particle. Devices can also be designed utilizing a twisted electric field rather than a twisted magnetic field. The performance of these electric devices will be so similar to that of the magnetic types that they will be mentioned only when explicit differences are to be noted.

The objects stated above have been obtained in the present invention by providing a magnetic field which has a particular spatial variation. A properly designed helical field source (a "corkscrew") can perturb an initially uniform axial field in such a way that there will be a monotonic increase (or decrease) in the transverse energy component of certain particles traversing the structure. The necessary design condition for the device is that the force resulting from the interaction of the axial particle velocity with the transverse component of the field perturbation be always approximately in the direction of the transverse particle velocity. It follows that there must be a close match between the local pitch of the device and that of the modified helical particle trajectory. This condition may be expressed as

$$p(z)=-2\pi m V_L(z)/qB_L$$

where B_L is the unperturbed axial field intensity, m, q and $V(z)$ are the mass, charge, and axial velocity of the particle, and $p(z)$ is the corkscrew pitch length at position z (p is negative for the left-handed structure of FIGURE 2). The helical field perturbation has no over-all effect on the axial field B_L; therefore, a change in the transverse particle energy necessitates a change in magnetic moment. The trajectory 11 in FIGURE 2 could apply to an ion moving from left to right or to an electron moving from right to left. If the direction of B_L is reversed from that shown in FIGURE 2 the trajectory 11 applies to an electron moving from left to right or to an ion moving from right to left. If the variable pitch coil 14 is wound as a right hand spiral (instead of left hand as shown in FIGURE 2), the terms ion and electron must be interchanged in the preceding two sentences; and the spiral trajectory becomes right handed. Reversing the polarity of source 15 connection to coil 14 reverses the direction of transverse flux B_T at any axial position z'. This reversal causes the trajectory 11 to rotate 180° in angle Θ about the z axis; otherwise, the trajectory is unaffected.

FIGURE 2 shows one form of a corkscrew device where a source for charged particles having some velocity energy has not been shown (the source may be located at either end of the corkscrew and may emit either electrons or positive or negative ions provided B_L is given the correct polarity and the particles have the correct entrance conditions). A load which uses the electron stream 11 has not been shown in order to avoid obscuring the basic corckscrew device. A field coil 12 energized by source 13 produces a longitudinal magnetic field B_L. A coil 14 of variable pitch p is immersed in field B_L with the coil axis z parallel to the field B_L. Coil 14 is energized by source 15 to produce a magnetic field having a component transverse to axis z. This transverse magnetic field varies in intensity and direction as a function of axial position inside coil 14 but as a first approximation may be considered to be directed normal to the z axis and normal to the conductor forming coil 14. Thus the transverse field has a spiral shape (or more correctly an auger shape) closely following the spiral of coil 14.

A transverse magnetic field which is twisted may be obtained in several ways. Most configurations, including the most practical ones, are not susceptible to analysis. As a result, an idealized case will be considered.

An infinitely long conducting ribbon wound into a helix with uniform pitch, radius r_0, carrying a current J, and w/p the fraction of cylinder surface covered by the ribbon, has fields on the axis given by $B_L=\mu_0 J/p$ and

$$\begin{Bmatrix} B_T \\ B_\theta \end{Bmatrix}=\frac{\mu_0 J}{p}\begin{Bmatrix} \sin \\ \cos \end{Bmatrix}\left(\frac{2\pi z}{p}-\theta\right)\left[\frac{\sin\left(\frac{\pi w}{p}\right)}{\left(\frac{\pi w}{p}\right)}\right]\left[\frac{r_0}{r_c}K_0\left(\frac{r_0}{r_c}\right)+K_1\left(\frac{r_0}{r_c}\right)\right]$$

where z and θ are the field coordinates with origin at a radius line passing through the center of the conducting ribbon, the K's are Hankel functions, and r_c is the cyclotron radius of the particle in the axial field. If desired, the expression is readily integrated with respect to r_0 to allow for a coil of finite thickness as well as width.

Although the above equation is for an infinitely long helix of constant pitch, the equation is useful in approximating the field configurations of a variable pitch helix since the field produced falls off rapidly with distance and a new pitch value can be used at different parts of the variable pitch helix.

It is seen that a transverse field which rotates with particle position is required. There are many ways in which this field can be produced. Among the simplest of these devices from a construction standpoint is an appropriate helix of magnetic material immersed in a magnetic field. A design which was successful in causing an electron beam to wind-up to an extent where approximately half of the energy was in the transverse energy component was constructed from a piece of mild steel bar stock, ⅛ inch thick by 30 inches long and tapered from a width of 0.5 inch at the center to zero at the ends in a cosine manner. The bar was wound into a helix of 1 inch inside diameter with a pitch length of 1 inch at the center decreasing in pitch as the ends are approached in a uniform manner so that the overall length is approximately four inches. The taper down to zero width at the ends of the coil provides a small transverse field so that the electron is not deflected from the axis by a large discontinuity in the field. The helix is constructed symmetrically about its center; the first half merely serves as an inlet structure to avoid spurious beam perturbations, the actual electron beam windup occurring in the exit half of the coil. The length of the effective part of the structure was approximately twice that calculated to be necessary to produce the wind up achieved. The excess length provides a mechanism for phase stability of the beam trajectory. This occurs because for any angular position of the electron, the value of transverse field will depend on the axial position of the electron. If the electron is advanced in axial position over its design position, the transverse field is stronger and reduces the axial velocity of the electron and similarly for an electron retarded in axial position where the transverse field is weaker.

FIGURE 3 shows the iron coil 31 with a coil 32 and energy source 33. The iron coil 31 is shown in cross section in order that the manner in which the radial field is produced may be illustrated. The longitudinal field B_L is produced by field coil 32 and was adjustable in the range of 100 to 300 gauss for the region inside coil 31. The ratio of transverse fiield intensity B_T to longitudinal field B_L was approximately 0.15 maximum along the axis. An electron gun (not shown) was used to introduce electrons 34 into the end of coil 31. Combinations of beam voltage (up to 1 kv.) and magnetic field B_L caused the electron beam to become a spiral closely approximating the spiral of the coil. The shape of the electron beam was observed by putting the corkscrew device of FIGURE 3 in a transparent chamber whose pressure was reduced to 1 micron. The ionization produced by the electron beam produced a visible indication of the path of the beam.

The spiral iron coil 31 of FIGURE 3 is shown in cross section to illustrate how the longitudinal field of coil 32 is distorted by spiral coil 31 to produce a radial field, B_T. Each cross section can be considered to be a small magnet which has a polarity as shown in FIGURE 3. It is seen that a transverse field component B_T will be produced which to an axially moving particle appears to rotate in a plane transverse to the longitudinal axis as the particle moves along the longitudinal axis.

The corkscrew of FIGURE 3 was used in conjunction with a magnetic mirror as shown in FIGURE 4. The coils 41 of the mirror when energized by sources 42 produced magnetic field lines 43 which were of the type indicated in the figure. A mirror ratio of 1.8, the ratio of the maximum flux density to the flux density at the center of the mirror, was obtained. The corkscrew 31 was placed in the relatively uniform field region in the center of the mirror and an electron beam 44 produced by source 45 was injected axially into corkscrew 31 at an energy up to 1 kv. The helical electron beam 46 produced by a proper combination of source 45 energy and field B_L was reflected by the mirror coils 41. This reflection by a mirror of ratio 1.8 indicated that over one-half the beam energy was in the transverse component of beam 46 before reflection. Changing either source 45 energy or field B_L resulted in no spiral 46 and the electron beam passed through mirror coil 41 without reflection. Reversing the direction of magnetic field B_L produced by coil 32 so that the handedness of coil 31 was wrong eliminated the spiral 46 and no beam reflection could be obtained.

It should be noted that the selectivity of the symmetrical structure discussed above is not good and the single structure can produce both large increases or large decreases in magnetic moment depending on the entrance conditions of the particle. This effect may be intolerable in certain applications.

A rotating transverse magnetic field can also be obtained by winding an electrically conductive material as a coil of variable pitch. The magnetic field produced when such a coil is energized has a transverse field which rotates with position along the coil. FIGURE 5 shows such a coil 51 in cross section energized by current from source 52. The magnetic lines 53 represent part of the magnetic field established around each conductor of coil 51. The heavy direction lines 54 represent the direction of the resultant radial field component with the length of the lines 54 representing the relative magnitude of this transverse component of field. It is seen that the radial field becomes smaller as the ratio of pitch to diameter is decreased. For many applications, a minimum pitch to diameter ratio of ⅓ will suffice. Although there is no theoretical limit on the amount of energy which may be transferred to the transverse component of energy, a practical engineering limit is about 75% of the energy in the transverse component.

The coil of FIGURE 5 has characteristics which may be undesirable in certain applications. Among these characteristics is the increase in longitudinal field strength in the region of the coil where the pitch is smallest. This effect may be minimized if the coil is being operated in a uniform relatively high field strength region which is produced by an external source (which is the usual situation). Another characteristic of the coil of FIGURE 5 is that it is difficult to obtain a smooth entrance condition for a charged particle entering the coil on the axis of the coil. The radial field existing on the axis tends to divert the particle from a helix centered about the coil axis, and to introduce spurious changes in its magnetic moment.

The variation in longitudinal field strength of the single conductor helix of FIGURE 5 can be avoided by using a bifilar winding with currents in the windings opposite in direction. This cancellation of longitudinal field also can be achieved by any arrangement of windings which has odd and even symmetry with respect to two orthogonal planes whose line of intersection is along the axis of the coil, where the odd and even refer to direction of current flow. An example of this type of construction is the quadrafilar winding shown in transverse section in FIGURE 6. In addition to the advantages of structural symmetry in termination and lead-in wires, the structure permits the adjustment in the strength of the transverse field, independent of the change in corkscrew pitch, merely by varying the spacing between pairs of conductors. Thus smooth entrance and exit conditions can be obtained easily and the transverse field adjusted for optimum performance.

FIGURE 6*a*, *b*, and *c* show how varying the spacing between the wires A, B, C and D while retaining symmetry about the X and Y planes can produce a transverse field 31 which differs in intensity but not direction. The direction is changed by twisting the wires along the longitudinal axis of cylinder 32.

A typical design of a quadrafilar type of corkscrew intended to function with an electron of 2 kev. energy with an axial field of 100 gauss is initial pitch—10 cm., diameter—11 cm., length—50 cm. The design was such that if all of the energy was in the transverse component of the electron, the diameter of the circle thus formed by the electron trajectory would be about 3 cm. Therefore, the design proceeded on the assumption that the transverse field had no radial dependence. The pitch varied in a cosine manner from the initial value of 10 cm. to an exit pitch of 2 cm. The current in the coil was approximately 160 amperes.

A corkscrew design useful for winding up an ion of hydrogen of 100 kev. energy may be on the order of 3 feet diameter by 300 feet in length. The greater mass and energy of the hydrogen ion as compared to the mass of electron is seen to require a much larger physical structure in order to cause the particle to wind up and have a substantial portion of its energy in the transverse velocity.

The designs of FIGURES 2, 3 and 6 are merely illustrative of the many possible coil configurations which can produce transverse fields which will cause a charged particle to wind up. It is not necessary for the coil to be wound on a cylinder of uniform diameter. A cone shaped coil with the smallest pitch near the largest end of the cone would be a configuration that may be more desirable than that shown in FIGURE 8 since the transverse field is strongest in the vinicity of the coil conductors. The equations of motion of the charged particle are such that almost any coil configuration with monotonic decreasing pitch will cause certain particles to wind up. Of course, the length of the coil required to cause the particle motion to become synchronous with the coil pitch and the dispersion of the beam at its exit point from the coil would depend upon how closely the pitch of the coil approximates the pitch that the charged particle wishes to follow while obeying the laws of Newton and Maxwell.

As the corkscrew is made longer, design becomes more critical if perfect resonance is to be maintained. In experimental coil configurations of 10 turns or less, the pitch variation was not matched properly to the equations of motion to give perfect resonance, yet over half the particle energy was easily transformed to the transverse component. Computer analysis shows that attempts to scale these same geometric configurations to longer systems would be unsuccessful since the energy transfer to the transverse component would decrease as resonance was maintained over a smaller fraction of the system length. In effect, the design would give a very long "zero beat" that, in a short system would look like perfect resonance. The longer system with its greater selectivity, however, would not tolerate the error. Zero beat is defined as that condition where the angle between the vectors representing the transverse field and the transverse velocity of the particle is not changing (a condition of resonance).

The quantity $(B_T B_L)(2\pi L/p)$, where L is the length of the corkscrew helix, is related to the fractional change in magnetic moment that can be produced by the corkscrew. A value of unity for this quantity has been found to be reasonable for designs that have been considered. The ratio of B_T/B_L determines the performance characteristics of the corkscrew. If B_T/B_L is large, then L/p is small and the helical coil will have only a few turns. For this case exact design details are not critical, a large change in magnetic moment can be produced, but the device will accept particles over a broad range of input conditions (not very selective), and there will be a significant effect on particles going through in the wrong direction (not very unidirectional). If on the other hand, B_T/B_L is small, the system can be highly selective and unidirectional, but since L/p will be large there will be many turns to the corkscrew. The design is very critical if resonance is to be maintained over the length of the corkscrew helix. In practical coils, a ratio of B_T/B_L in the range of 0.1 to 10% is most likely to be useful with a value of 1% considered about right for thermonuclear applications. Since B_T has a radial dependency, the change in the ratio B_T/B_L as the particle spirals away from the axis must be considered in the design.

Corkscrew devices can be constructed which use a twisted electric field rather than a twisted magnetic field. An electric field device is shown in cross-section in FIGURE 7 where the bifilar winding of conductors 41 and 42 is energized by voltage source 44 to produce a twisted electric field 43. A longitudinal magnetic field is also used. There is no essential difference between the electrostatic and magnetic corkscrews except that in the electrostatic case the total particle energy may change by an amount not exceeding the voltage applied between the conductors. This possible increase of energy and details of the electric field distribution introduce more considerations into the design of the corkscrew.

FIGURE 8 shows a possible application for the corkscrew device where it is desired that a charged particle emerge with a predominantly axial velocity from the corkscrew. A charged particle source 81 emits a beam of particles 82 which enter a section of a particle accelerator 83 wherein a beam of high energy particles 84 is traveling along the axis z. The beam 82 has a transverse and axial component of velocity relative to axis z because of the necessity for placing the source 81 off axis z. The corkscrew coil 14 and the field from solenoid 12 convert the transverse velocity component into a longitudinal velocity so that beam 82 merges with beam 84 (essentially unaffected by the corkscrew) to form axial beam 85 whose particles are further accelerated. Thus, it is seen that the corkscrew can function as a charged particle "unwinder" as well as a "winder."

Another application of a corkscrew used as an unwinder is to supply a monoenergetic charged particle beam. Modification of FIGURE 8 may be made so that there is no beam 84 and section 83 is sealed at the end near the source 81. A beam 82 from source 81 will contain charged particles having a range of energies centered about some center value. In addition there will be some angular dispersion of energy. If this beam is sent through the corkscrew structure of FIGURE 8 and unwound and the corkscrew is selective, the beam 85 emerging from the corkscrew will be essentially monoenergetic and with very little angular dispersion. The selectivity of the corkscrew is obtained by making it considerably longer than necessary and designing its pitch to be a close approximation of the pitch of the spiral path of the charged particle.

Although the invention has been described in terms of a device in which a coil of monotonically changing pitch and uniform axial field intensity have been used, this is not a necessary limitation. A coil in which the pitch changes in discrete steps will function to cause particle windup although not so effectively as a continuously changing pitch coil. Also, there is no absolute requirement that the axial field B_L be uniform in intensity throughout the length of the variable pitch coil. Of course, since pitch of a charged particle changes with B_L the coil pitch must be varied accordingly to match the new particle pitch.

While the invention has been disclosed in specific embodiments and uses, it will be apparent to those skilled in the art that numerous variations and modifications may be made within the spirit and scope of the invention and it is not intended to limit the invention except as defined in the following claims.

What is claimed is:

1. A device for changing the magnetic moment of a charged particle moving in a static magnetic field with a definable axis comprising means to supply a field transverse to the axis of said static magnetic field at the location of said particle whereby forces act on said particle to change its path and means to change the direction of said transverse field in accordance with the changing location of said charged particle, along a helical path characterized by decreasing pitch with increasing radius.

2. A device for changing the magnetic moment of a charged particle moving with a velocity along a helical trajectory in a static magnetic field having a definable axis comprising, a variable pitch helical coil with spaced turns having its longitudinal axis lying along the axis of said field, means for energizing said helical coil to produce a static helical field having field components radially transverse to said axis and changing in direction as a function of position along said axis to form a twisted field having a changing pitch along said axis closely matching the changing pitch of the trajectory of said charged particle, said twisted field radial component being normal to and coincident with the axially transverse component of velocity of said particle on the particle trajectory, whereby forces are exerted on said particle to cause said change in its pitch and magnetic moment.

3. A device for causing a charged particle to follow a prescribed trajectory comprising means for producing a static magnetic field having a direction and an axis of symmetry, an electrically conductive helix with spaced turns and a longitudinal axis along said axis of symmetry, said helix producing a field transverse to said longitudinal axis when energized by a source of electrical energy, said transverse field spiralling about said longitudinal axis to correspond to the spiral of said helix, a source of charged particles to inject said particles into said helix, said helical field and magnetic field coacting on said charged particles to cause the particle to assume a trajectory of helical form, the pitch of said trajectory approaching the pitch of said helix at least as the particle exits from said helix.

4. A device for changing the magnetic moment of a

charged particle moving on a trajectory in a non-time-varying magnetic field having a definable axis comprising means for establishing a non-time-varying helical magnetic field having field components transverse to said axis which change in direction as a function of position along said axis to form a twisted magnetic field with a pitch along said axis closely matching the changing pitch of the trajectory of said particle moving in said helical field, whereby the magnetic moment of said particle is increased when said trajectory pitch is decreased and decreased when said pitch is increased.

5. A unidirectional device for changing the magnetic moment of a charged particle comprising, a variable pitch helical coil of electrically conductive material, the diameter of said coil being not greater than three times the minimum pitch of said coil, a current source connected to said coil to establish a magnetic field having components transverse to the axis of said coil to form a transverse field configuration having the same general pitch as that of said helical coil, means for producing a second magnetic field directed along said coil axis, a source of charged particles adapted to propel said particles into one end of said coil with a trajectory pitch approximating that of said coil end, and means controlling said current source whereby said transverse helical field and said second magnetic field force said particles to take a helical trajectory whose pitch is substantially the same as the pitch of said coil.

6. A device for changing the magnetic moment of a charged particle moving on a helical trajectory in a static magnetic field with a definable axis comprising a helical coil of ferromagnetic material of variable pitch, said material being smaller in width than said pitch so that there is a space between adjacent turns of said coil, said coil having a longitudinal axis coincident with the axis of said static magnetic field, said coil establishing a secondary magnetic field having helical field components transverse to said axis which change in direction as a function of position along said axis to form a twisted field along said axis closely matching the changing pitch of the trajectory of said particle moving in said helical field, whereby the magnetic moment of the charged particle is increased for particle motion through said coil in the direction of decreasing pitch and decreased for particle motion in the direction of increasing pitch.

7. The device of claim 6 wherein said secondary magnetic field is the localized distortion of the static magnetic field entering and leaving said ferromagnetic material.

8. The coil of claim 6 wherein said ferromagnetic material is a permanent magnet with the polarity in the longitudinal direction after winding in coil form.

9. A device for changing the magnetic moment of a charged particle moving along a helical trajectory in a constant magnetic field whose direction defines an axis, comprising a variable pitch helical coil having electrically conducting spaced turns, said coil having its longitudinal axis lying along the axis of said field, means for causing a flow of direct current through said coil to establish a helical magnetic field having field components transverse to said axis which change in direction as a function of position along said axis to form a twisted field with a variable pitch along said axis closely matching the changing pitch of the trajectory of said charged particle moving in said helical field, whereby the magnetic moment of the charged particle changes from one prescribed value at the entrance to said helical coil to a second prescribed value at the exit.

10. A device for changing the magnetic moment of a charged particle moving in a static magnetic field comprising means for establishing a variable pitch helical electrostatic field having field components transverse to the axis of said helix and changing in direction as a function of position along said axis to form a twisted electric field, means for producing a magnetic field in the direction of said axis, and means for injecting charged particles into said helical electrostatic field with a trajectory corresponding to the pitch of said helix whereby said electric field and said magnetic field force said particle to take a helical trajectory whose pitch follows that of said helical field.

11. A unidirectional device for causing the trajectory of an electron beam to wind-up comprising a variable pitch helical coil of electrically conducting spaced turns energized to produce a magnetic field having components within said coil transverse to the longitudinal axis thereof, said coil being wound in a counter-clockwise direction, an electron gun emitting a beam of electrons with a selected entrance velocity directed along said longitudinal axis, said electrons entering said coil at the end of greatest pitch, a source of uniform magnetic field directed along said axis and extending throughout said coil, said uniform field polarity being adapted to give said electrons a counter-clockwise rotation, said electrons being diverted from a path along said axis by said transverse and longitudinal fields to assume a helical trajectory of decreasing pitch matching said variable pitch helical field as the electron progresses with increased magnetic moment along said axis.

12. A device for changing the magnetic moment of a charged particle moving along a trajectory in a magnetic field comprising, means to supply a non-time-varying first magnetic field whose lines of force are substantially unidirectional, means to supply a second non-time-varying magnetic field having an axis of symmetry, said second field having at least a component normal to said axis, said normal component helically spiraling along said axis with changing pitch, whereby said moving charged particle is caused to assume a spiral trajectory around said axis corresponding to said spiraling normal field component.

13. A device for changing the magnetic moment of a charged particle moving with velocity in a static magnetic field comprising means for producing said static magnetic field, a helical coil having a longitudinal axis, means for energizing said coil to produce a static field component radially transverse to the axis of the coil, said radial field component changing direction along the axis of the coil to have a pitch substantially the same as the pitch of the coil, said radial field component causing said particle to change its velocity in a direction transverse to said coil axis, said transverse particle velocity being acted upon by the axial field of the coil and said static magnetic field to oppositely change its axial velocity to maintain the particle at a constant velocity, the change in axial and transverse velocities causing said particle to assume a helical trajectory corresponding to the helix of said coil.

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