Sept. 8, 1959 J. W. GALLOP 2,903,578

TRAVELLING WAVE LINEAR PARTICLE ACCELERATORS

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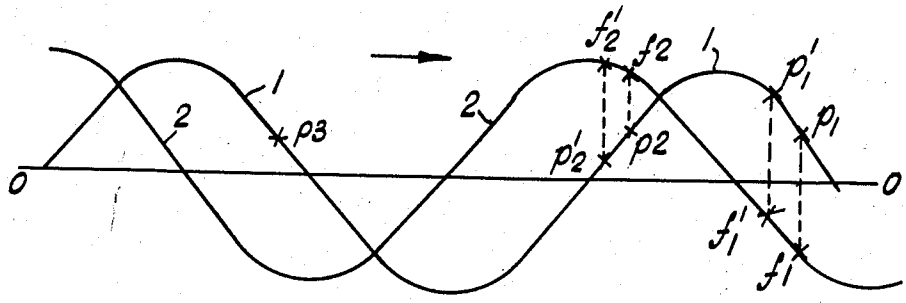


FIG. 1.

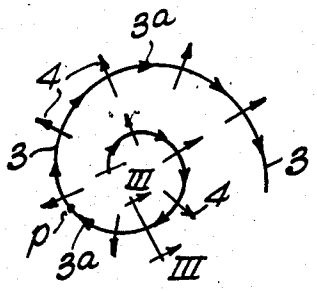


FIG. 2.

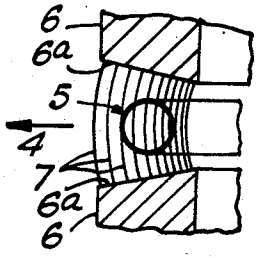


FIG. 3.

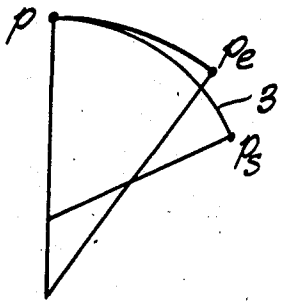


FIG. 4.

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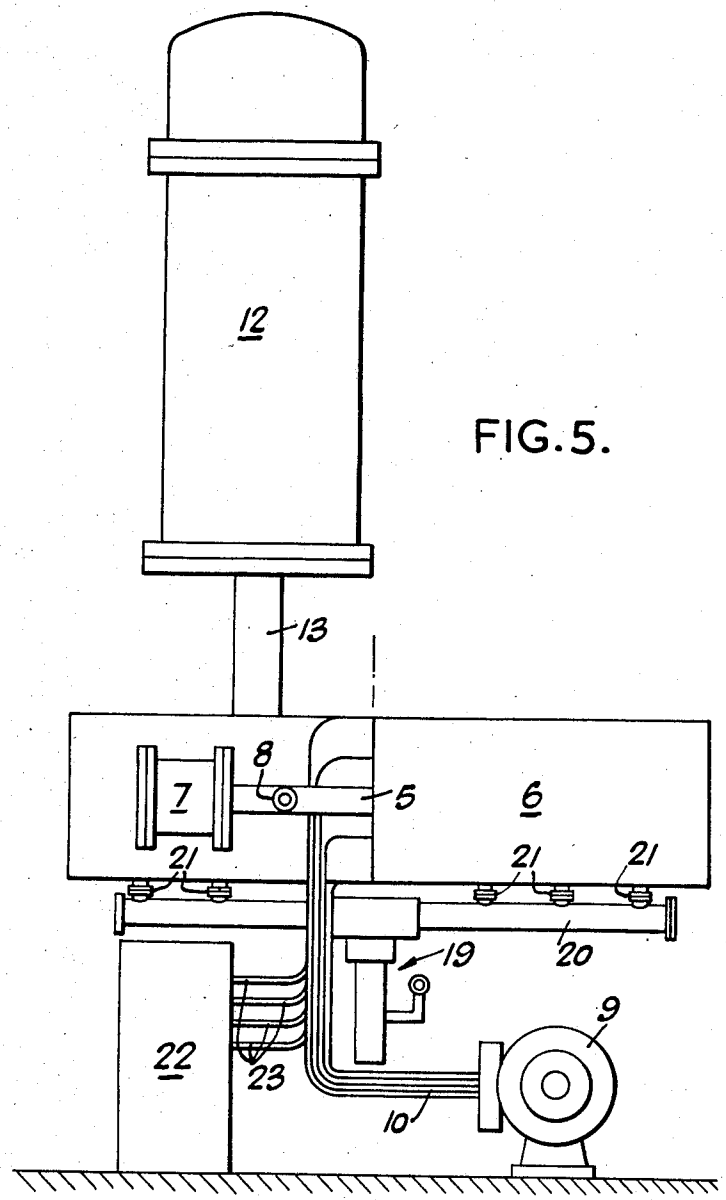


FIG. 5.

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Fig. 6.

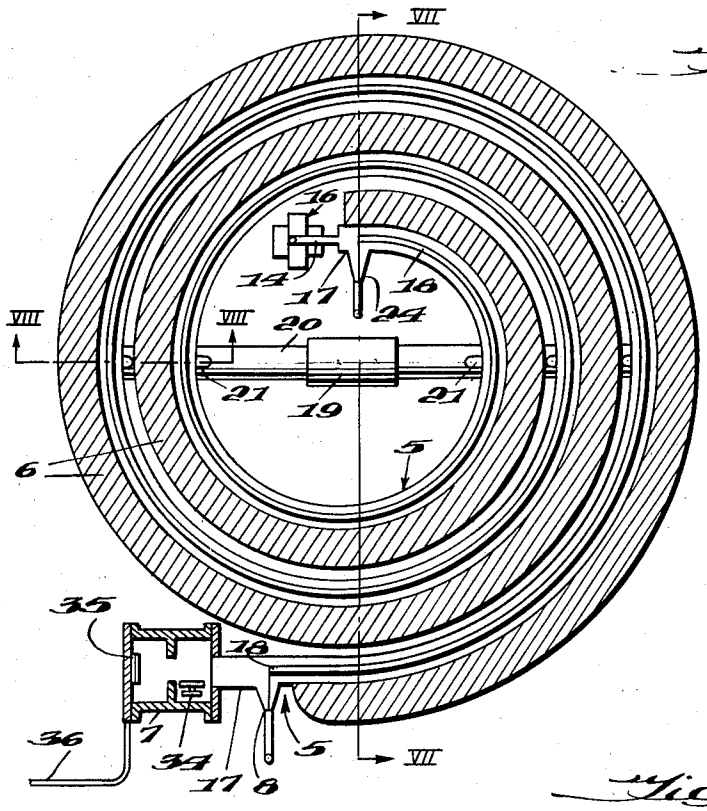
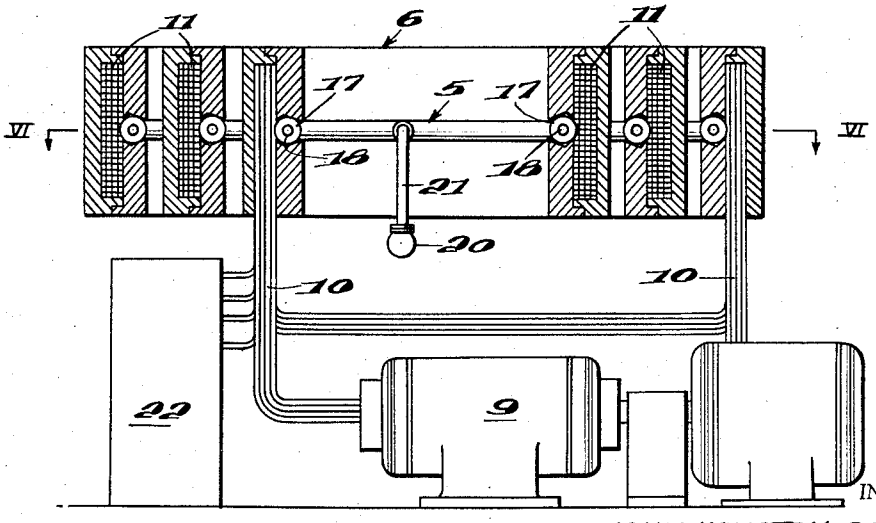


Fig. 7.



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Fig. 8.

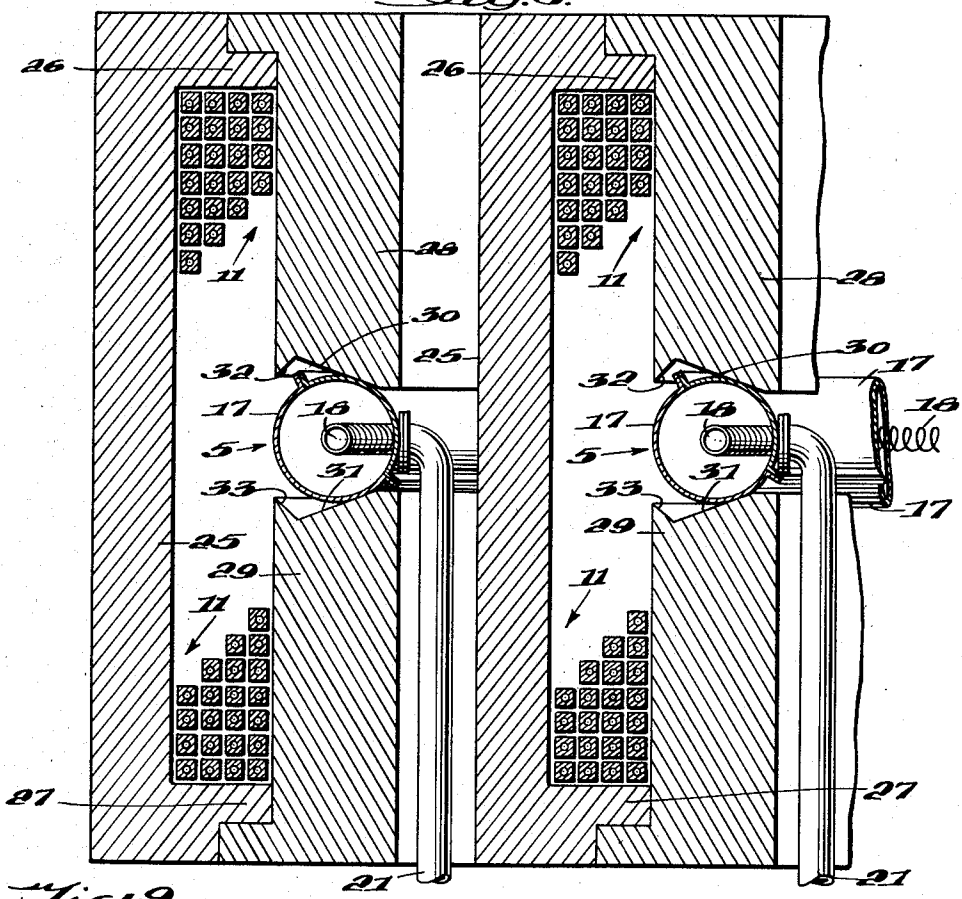


Fig. 9.

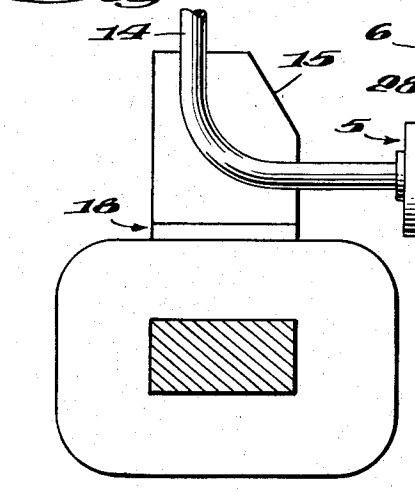
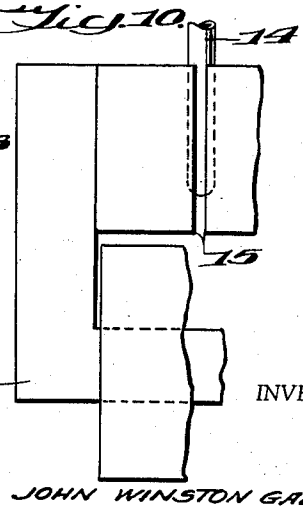


Fig. 10.



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TRAVELLING WAVE LINEAR PARTICLE ACCELERATORS

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Application October 19, 1953, Serial No. 386,995

Claims priority, application Great Britain October 21, 1952

13 Claims. (Cl. 250—27)

This invention relates to travelling wave linear particle accelerators for accelerating nuclear or other atomic particles such as electrons, protons, and the like to energy levels greater than those normally obtainable from known types of linear accelerator having a slow wave structure as the electric field generator, and at values of current higher than are obtainable from such devices as synchro-cyclotrons and proton synchrotrons. By "slow wave structure" is meant a propagating element or conductor to which radio frequency energy is fed so as to set up, along the axis thereof, a travelling electric field pattern the velocity of which may be controlled by the properties of the structure.

Travelling wave linear accelerators for producing relatively high energy protron beams are known in which the particles travel on the leading edge of the accelerator wave form. Since, in this region, the particles are subjected to a radial defocussing electric field, the particles of a beam rapidly become dispersed, and it has been proposed to direct an electron beam along the axis of the slow wave structure against the direction of travel of the wave in order to counteract the defocussing effect of the said radial electric field. There are practical limitations to the output from such a device, however, and it is an object of the present invention to provide a travelling wave linear accelerator which does not suffer from this disadvantage.

The present invention resides essentially in the provision of a continuous time-invariable magnetic field embracing, and extending without interruption for the full length of the electric accelerating field generator, the magnetic field vector lying transverse to the path of a particle being accelerated while its field strength decreases progressively across the path in a direction at right angles to the said vector.

According to one feature of the present invention, a travelling wave linear accelerator for nuclear and other atomic particles has the slow wave structure disposed about a curvilinear axis representing the stable orbit of a particle being accelerated, a time-invariable magnetic field being applied transversely to the said curvilinear axis to constrain a particle to travel substantially therealong and having an intensity which decreases progressively in the radially outward direction with respect to the centre of curvature of the axis.

The slow wave structure—which may be a wave guide or a coaxial line having its centre conductor wound in the form of a helix of variable pitch, both being fed at the input end from an R.F. generator—is preferably bent about a spiral axis and located between a pair of magnet pole systems the pole faces of which diverge radially outwards with respect to the origin of the spiral.

In the accompanying drawings:

Figure 1 shows the distribution of radial and accelerating electric fields associated with an electro-magnetic travelling wave;

Figure 2 illustrates the stable orbit of a particle being accelerated in a magnetic field normal to the plane of the figure;

Figure 3 is a schematic cross-section of a device according to the present invention, taken on a line such as III—III of Figure 2;

Figure 4 is a geometrical analysis of the behaviour of a particle being accelerated in a device such that indicated in Figure 3;

Figure 5 is a side elevation showing the general assembly of apparatus such as that envisaged in Figs. 2 and 3;

Figure 6 is a plan view, partly in section, of the apparatus shown in Fig. 5 but with the upper magnet pole removed;

Figure 7 is a cross-section on the line VII—VII of Figure 6;

Figure 8 is a cross-section on the line VIII—VIII of Figure 6, and

Figures 9 and 10 are fragmentary sectional and end elevations, respectively, of a particle input deflector magnet.

Referring first to Figure 1 of the drawings, the accelerating wave travelling along a guide is represented by the wave form 1 (here shown as part of a sine wave). Associated with this accelerating field there is a radial field the distribution of which along the guide is the differential of the accelerating field and is therefore represented by the cosine wave form 2. Positive half-cycles of the latter represent a radially inward or focusing field while negative half-cycles represent a radially outward or defocusing field with respect to the axis O—O of the guide. In travelling wave linear accelerators as hitherto constructed, the particles to be accelerated have normally been located, for stable equilibrium conditions, on the leading edge of the wave form 1 as indicated, for example at p_1. (The travelling wave is assumed to be moving in the direction of the arrow in the figure.) A particle at the position p_1 which tends to lose energy begins to lag in phase with respect to the accelerating field 1 and thereby moves into a zone of greater electric field as indicated p_1', thereby acquiring increased energy. Similarly, should a particle initially at p_1 gain energy, it will begin to lead in phase with respect to the accelerating field 1 and will move in the opposite direction to a position of lower accelerating field intensity. As will be apparent, however, from the figure, particles in the position shown at either p_1 or p_1' are subjected to a defocusing electric field as indicated by the corresponding values on the curve 2 at f_1 and f_1' respectively, and the beam of particles becomes rapidly divergent.

If, however, the particles could be constrained to travel in the accelerating field 1 at positions such as p_2, it will be evident that they will be subjected to a focusing field represented by the point f_2 on the curve 2. The position p_2, however, is an unstable position because, should a particle in that position lose energy, it will, as before, lag in phase on the accelerating field 1 and will move to a position such as p_2' in which it is subject to a decreased accelerating field while also experiencing an increased focusing field, indicated by the point f_2' on the curve 2. The particle will, therefore, continue to lag by an increasing amount on the accelerating field 1 until it has fallen back to some position such as that corresponding to the point p_3 on the succeeding positive half-cycle of the accelerating field 1. The following analysis is valid whatever the velocity of the particle so long as the mass is understood to be the relativistic mass.

It is a well known principle which is embodied in such apparatus as the cyclotron that a particle moving with linear velocity in a transverse time-invariable magnetic field describes a curved path or orbit with an angular velocity which is a function of its mass, charge, and the

strength of the magnetic field. As the velocity of the particle increases, and assuming that the field remains constant, the radius of the orbit increases. Similarly if the particle loses velocity, the radius of the orbit decreases. This physical principle is applied according to the present invention to a linear accelerator in order to impart stability to a particle which is travelling in the position p_2 of Figure 1 in an accelerating field.

This result is achieved by bending the accelerating wave structure (which may be a wave guide or a coaxial line having a helical inner conductor as indicated above) so that its axis forms a spiral such as that indicated at **3** in Figure 2. The arrow heads **3***a* on the spiral **3** indicate the direction of travel of a particle *p* when following the stable path, while the arrows 4 which are transverse to the path **3** indicate the direction of decrease of intensity of an applied magnetic field which follows continuously the path **3**. Figure 3 shows schematically how this concept is carried out in practice, the circle **5** indicating a cross section through the slow wave structure while the parts shown fragmentarily at **6** represent magnetic poles giving rise to a time-invariable magnetic field represented by a family of curved lines **7**. It will be seen that the pole faces **6***a* of the magnetic poles **6** are divergent radially outwards in the direction of the arrow **4** so that the intensity of the magnetic field within the slow wave structure **5** decreases in intensity in the same direction. This is indicated graphically by the progressively increased spacing of the lines **7**.

Figure 4 shows a geometrical analysis of the behaviour of a particle traversing an elemental section of the structure **5** in Figure 3. Starting from the point *p*, a particle which moves in phase with the accelerating wave form in Figure 1—i.e. remaining with respect thereto at a point such as p_2—follows the stable orbit **3** to reach the point p_s. Should the particle acquire increased energy, its actual orbit will deviate from the stable orbit **3** so that after a given time the particle will reach the point p_e where it has moved on an increased radius relative to the stable orbit. At this point, however, the particle is experiencing a less intense magnetic field so that its angular velocity is decreased and it tends to lag on the accelerating field. Similarly, a particle which loses energy travels on a path of less radius than the orbit **3** and enters a magnetic field of greater intensity, thus beginning to lead on the accelerating field. These are the conditions required for stability of a particle travelling at a point such as p_2 in Figure 1.

The object of constraining the particle to travel in a region corresponding to the point p_2 on the travelling wave **1** is to remove it from the defocusing field which it experiences in regions corresponding to the point p_1. A magnetic field of the form indicated in Figure 3 is of itself a focusing field and adds to the electric focusing field arising from the travelling wave (see curve **2** in Figure 1). While both tend to increase the current density (and hence the number of particles being accelerated) the electric focusing field opposes the mechanism for phase stability, since it opposes any particle having an excess or deficit of energy from leaving the stable orbit **3** and thus entering a region of lesser or greater magnetic field. There is a direct relationship between the electric focusing (or defocusing) forces and the accelerating force. In any practical design of accelerator according to the present invention, therefore, there will be a conditional relationship between the accelerating force and the magnetic field gradient. It can be shown that this relationship can be specified by equations which define the phase angle $\theta_{2\,max} - \theta_{1\,min}$ over which particles will be captured:

$$\theta_{2\,max} \leqslant \cos^{-1} \frac{2\lambda_s E}{\pi r_0^2 F_0}(n-1)$$

$$\theta_{1\,min} \geqslant \cos^{-1} \frac{2\lambda_s E}{\pi r_0^2 F_0} n$$

where:

λ_g=wavelength of the accelerating field in the slow wave structure;

E=kinetic energy of the particle;

r_0=maximum value of the electric accelerating field ×charge on the particle;

$$n = \frac{r_0}{H_0}\frac{dH}{dr}$$

From the equations it can be seen that n can be made greater than 1 by reducing $\theta_{2\,max}$.

Figures 5 to 10 illustrate in greater detail one practical embodiment of the invention. Figure 5 shows the output end of the slow wave structure **5** provided with a target box **7** of conventional design and a connection **8** to an R.F. output matching device or feedback system, again of conventional design and not shown. The magnetic field system is energised by a D.C. generator **9** coupled in the circuits of some of the end connections **10** of the magnet winding (indicated generally at **11** in Figures 7 and 8). The particles to be accelerated are derived from a primary accelerator **12** (which may for example, be a Van de Graaff machine) having a vertically downward output **13**. This leads to an injection tube **14** (Figs. 6, 9 and 10) which passes through a right angle between opposed pole faces **15** of a D.C. deflector magnet **16**, and terminates within the outer conductor **17** of a spiral coaxial line **5** which constitutes the slow wave structure for producing the electric accelerating field. The inner conductor **18** is wound in the form of a helix of gradually and progressively increasing pitch.

The space within the coaxial line **5** is maintained at low pressure by a vacuum pump **19** through a trunk **20**, which underlies the coaxial line **5** parallel to a radius thereof, and pipe connections **21**. The conductors **11** of the main magnet winding are hollow, water or other liquid coolant being circulated therethrough by means of a pump **22** and tee-off connectors **23** (Fig. 5).

The line is fed with R.F. energy through an input coupling **24**.

The main magnet structure **6** consists of a core which is of elongated substantially **C**-shaped cross-section, the yoke part **25** (Fig. 8) being located vertically on the outside of the coaxial line **5** and following the contour of the latter from the R.F. input coupling **24** to the R.F. output couyling **8**. The yoke **25** has upper and lower stepped return portions **26, 27** respectively, the steps serving to register detachable upper and lower pole pieces **28, 29** which constitute the limbs of the **C**. These pole pieces are removable in a direction parallel to the yoke **25** so that assembly of, and access to, the spiral coaxial line **5** is facilitated.

The adjacent end edges of the pole pieces **28, 29** are chamfered as shown at **30, 31** in the drawings, so that the magnetic field strength falls off progressively across the coaxial line from a maximum at its radially inward side to a minimum at its radially outward side. A short return chamfer or lip **32, 33** is formed at the maximum gap edge of each pole face **30, 31** this lip serving to control the form of the magnetic field.

It is to be understood that only some of the conductors **11** are shown in position in Figure 8 for clarity of representation of the core structure.

The magnet structure may be built up in arcuate sections for simplicity of construction and ease of handling. Similarly, the energising winding conductors **11** may be of sectional form. The end of one conductor is connected to the start of another by the end connections **10** in Figure 7. As will be understood, groups of series connected conductors may be paralleled, each group being then connected direct to the existing current generator **9**.

The target box **7** for receiving accelerated particles may be replaced by any other desired output device for example, where the accelerator is to be used for deep-ray

therapy, a suitable termination for directing the particle onto a patient would be substituted, as will be understood. In the arrangement illustrated, the box has the usual moveable closure member 34 and water-cooled target holder 35, water being circulated through pipes as indicated at 36.

In a typical design of accelerator according to the present invention for accelerating protons, the following data apply for a spiral having 2½ convolutions as illustrated:

Output energy	m.e.v.	24
Injection energy	m.e.v.	3
Mean mag. field strength	kgauss	6
R.F. power input	mw. pulsed	1

From curve 2 in Figure 1 it can be seen that the electric focusing or defocusing forces vary according to the position of the particle with respect to the travelling wave. In practice, the particles will be accelerated in bunches, each oscillating over a range of phase angle roughly symmetrical about a mean position p_2. In order to keep these bunches as large as possible, it is desirable that advantage be taken of the presence of magnetic focusing when the electric field becomes zero or defocusing. This, together with the previous condition, would in practice fix the numerical relationship between the magnetic field configuration and the value of the accelerating force.

From the above description and analysis it will be apparent that the invention provides a construction and arrangement of linear particle accelerator which is capable of producing a concentrated beam of high energy particles. These particles can be made to have not only a higher energy than can be obtained from known forms of linear particle accelerator employing a slow wave structure, but for a given energy level, they will be produced at higher current values (of the order of those obtainable from a fixed frequency cyclotron) than are obtainable from a synchrocyclotron or a proton synchrotron, since, by comparison, the latter can only be run at a much lower recurrence frequency.

What I claim is:

1. A travelling wave linear particle accelerator comprising an electric accelerating field system consisting of a coaxial line arranged in a flat spiral increasing in radius from the particle injection end to the particle emission end, the inner conductor being in the form of a helix of progressively increasing pitch, and a time-invariable magnetic field system embracing the electric field system and having opposed pole pieces which embrace the spiral coaxial line continuously throughout its length, the pole faces being shaped so as to be mutually divergent in a radially outward direction with respect to the spiral and symmetrical with respect to the medial plane of the spiral line.

2. A travelling wave linear particle accelerator as claimed in claim 1 wherein the pole pieces are constituted by the limbs of a magnet core whose cross-section is generally C-shaped, the yoke of the core lying to one side of the coaxial line and following the contour thereof at constant spacing from the outer conductor, electrical conductors for the magnet energizing current being located in the recesses between the limbs and the yoke and the circuit through the energizing winding being completed by cranked end connections joining the end of one turn with the beginning of another and crossing the convolutions of the spiral line in a plane parallel to the medial plane of the spiral.

3. A travelling wave linear particle accelerator as claimed in claim 2 in combination with a particle beam input device for injecting particles into the coaxial line at the start of the spiral and an output terminal for collecting and utilizing the accelerated particles at the outer end of the spiral.

4. A travelling wave linear particle accelerator as claimed in claim 3 wherein the beam input device comprises a magnetic deflector for bending a beam of particles through an angle in a plane which intersects the medial plane of the spiral.

5. A travelling wave linear particle accelerator as claimed in claim 4 including a source of particles having a velocity above which they are to be accelerated, the said source being connected to the magnetic deflector for injecting the particles into the coaxial line.

6. A travelling wave linear particle accelerator having an electric accelerating field system comprising a coaxial line bent to form a spiral lying in a single plane, the inner conductor being formed as a helix of progressively increasing pitch, a radio-frequency generator coupled to the coaxial line at the start of the spiral, means for injecting particles to be accelerated into the start of the spiral line, and means for receiving accelerated particles at the outer end thereof, and a magnetic field system comprising a magnetic core of substantially C-shape in transverse cross-section extending continuously along the spiral line so that the limbs of the C lie on opposite sides of the outer conductor of the coaxial line with the common axis through the limbs normal to the plane of the spiral, said limbs having their opposed end faces chamfered so as to provide a gap which diverges radially outwards with respect to the spiral, a magnet energizing winding comprising a plurality of conductors located in the recesses between the limbs of the C and the yoke portion thereof, and cranked end connections lying in a plane substantially normal to the plane of the spiral and connecting the outer end of one conductor with the start of another, and a source of direct current for energizing the magnet winding inserted into at least one cranked end connection.

7. A travelling wave linear particle accelerator as claimed in claim 6 in which the spiral coaxial line has more than one convolution, and a vacuum trunk is located close to and parallel with the plane of the spiral and extends parallel to the radius of the spiral, the trunk being connected to the space within the outer conductor of the coaxial line for maintaining the required low gas pressure within the line.

8. A travelling wave linear particle accelerator as claimed in claim 7 wherein the particle beam injection means comprises a high energy particle beam generator having its output located in a plane normal to the plane of the spiral and tangential to the axis thereof at the start, and a deflector magnet having its poles disposed symmetrically about the said normal plane, the input end of the gap therebetween being collinear with the generator output and the output end collinear with the start of the coaxial line.

9. A travelling wave linear particle accelerator comprising in combination an electric accelerating field system consisting of a coaxial line arranged in a flat spiral increasing in radius from the particle injection end to the particle emission end, the inner conductor being in the form of a helix of progressively increasing pitch; a time-invariable magnetic field system embracing the electric field system and having opposed pole pieces which embrace the spiral coaxial line continuously throughout its length, the pole faces being shaped so as to be mutually divergent in a radially outward direction with respect to the spiral and symmetrical with respect to the medial plane of the spiral line; means for feeding radio-frequency energy into the coaxial line at the start of the spiral; and a matched termination for absorbing R.F. energy at the outer end of the spiral.

10. A travelling wave linear particle accelerator having an electric accelerating field system capable of generating a travelling wave of increasing phase velocity from an input to an output end of the system and following a curvilinear path of progressively increasing radius from a particle injection end to a particle emission end, and a time-invariable magnetic field system having opposed poles each of which extends lengthwise of the particle path and continuously therealong, the pole faces

diverging in a direction at right angles to the path so as to cause the field strength in the gap to decrease across the path in the direction of deviation from the mean path of a particle acquiring excess energy, said decrease being such that a particle acquiring excess energy is constrained to travel in a focusing region of the electric field.

11. A travelling wave linear particle accelerator comprising a slow wave structure capable of generating a travelling wave of increasing phase velocity and disposed about a curvilinear axis whose radius of curvature increases progressively from a particle injection to a particle emission point; a magnetic field system embracing the said structure continuously throughout its length from the point of injection to the point of emission, and including continuous opposed pole faces having a substantially constant spacing along the axis of the said structure and diverging outwardly in the direction of the radius of curvature of the said curvilinear axis; and means for energising said magnetic field system so as to produce a time-invariable field across the axis of the slow wave structure whereby a particle which deviates from the stable path as a result of its acquiring an excess of energy is subject to a reduced magnetic field intensity tending to return it to the stable path.

12. A travelling wave linear particle accelerator comprising a slow wave structure of spiral form capable of generating a travelling wave of increasing phase velocity; a radio-frequency input to the structure for producing said travelling wave; a magnetic field system extending continuously along the axis of an embracing the said structure and having pole pieces disposed on opposite sides of the mean plane of the spiral for maintaining across the slow wave structure a magnetic field intensity which is substantially constant along the length of the said structure but of progressively decreasing value transversly thereof in the radially outward direction of the spiral; and means for maintaining a time-invariable flux between the pole pieces.

13. A travelling wave linear particle accelerator comprising a spiral slow wave structure whose axis defines the mean stable orbit of a particle being accelerated, and capable of generating a travelling electric accelerating wave of progressively increasing phase velocity; means for injecting particles axially into said slow wave structure; a radio-frequency generator for energising said structure to produce said travelling electric accelerating wave; a magnetic field system having opposed north and south poles disposed so as to embrace said slow wave structure symmetrically on either side of a plane containing the axis of said structure and extending continuously therealong from the particle injection end to the particle emission end, said poles being shaped so as to cause a reduction in magnetic field intensity across the said structure in the direction of deviation from the mean stable path of a particle acquiring excess energy, whereby to reduce the excess energy of said particle and cause it to return to the stable path; and means for time-invariably energising said magnetic field system.

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