Dec. 16, 1952 J. L. LAWSON ET AL 2,622,194

APPARATUS FOR ACCELERATING CHARGED PARTICLES

Filed Nov. 18, 1950 3 Sheets-Sheet 1

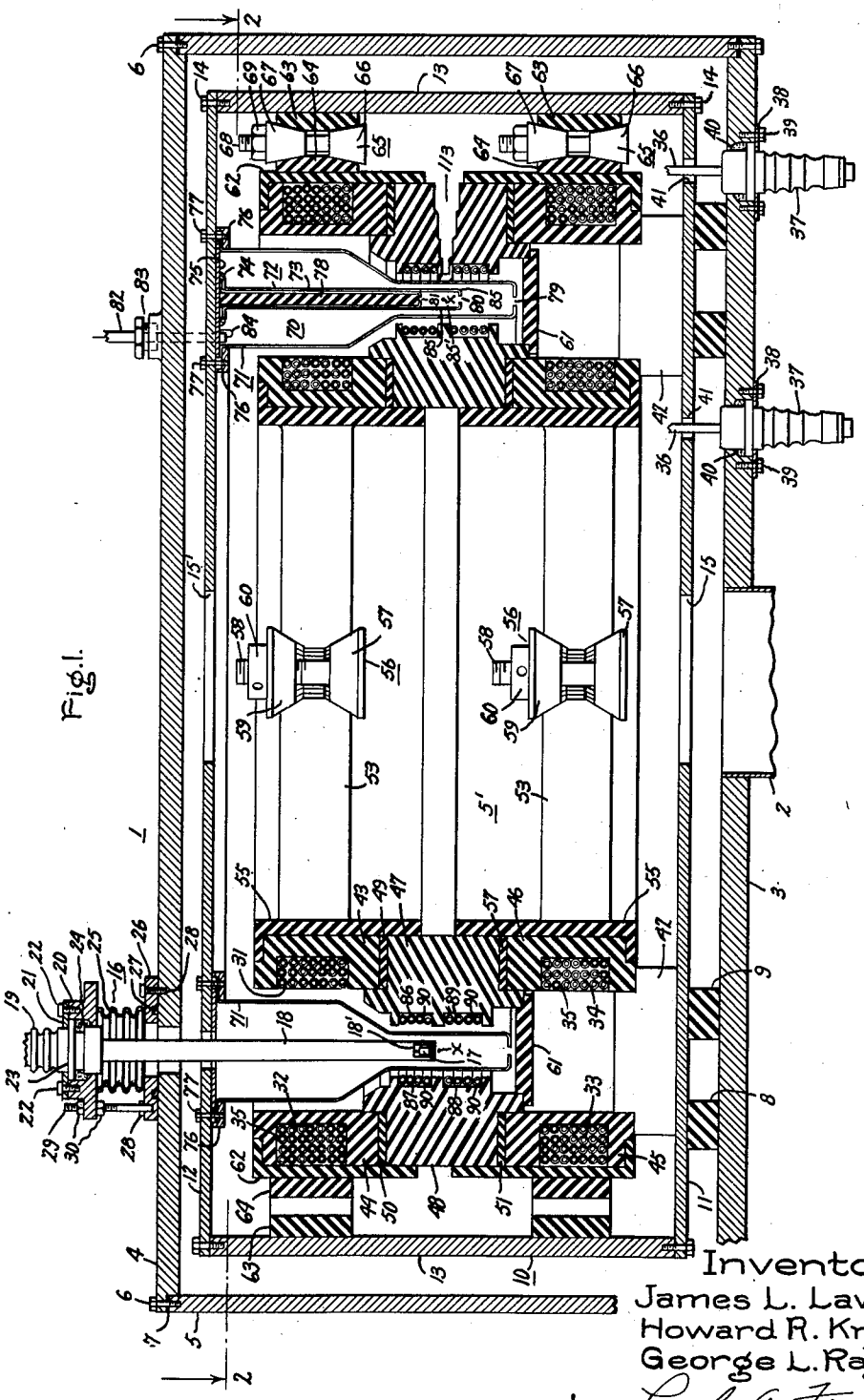


Fig. 1.

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Fig. 2.

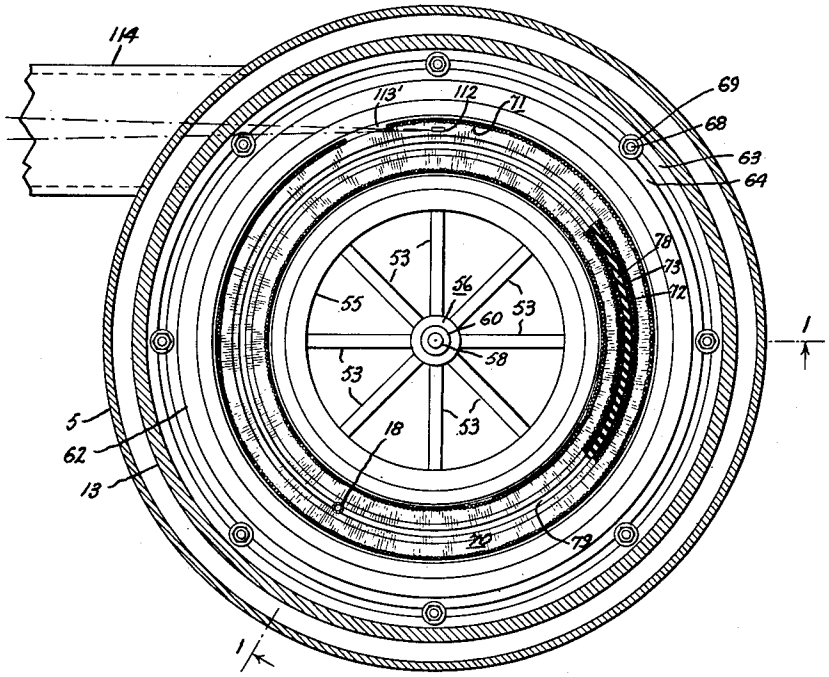


Fig. 3.

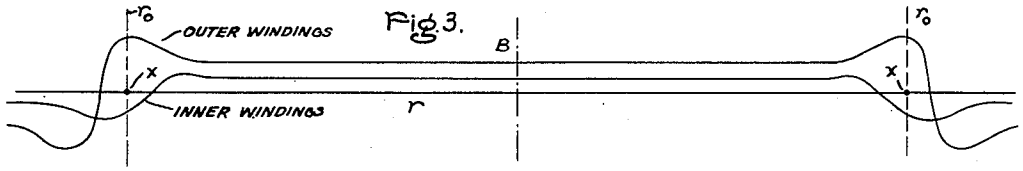
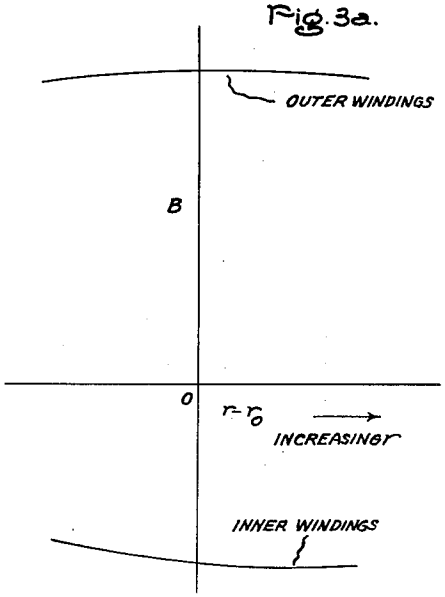


Fig. 3a.



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Fig. 4.

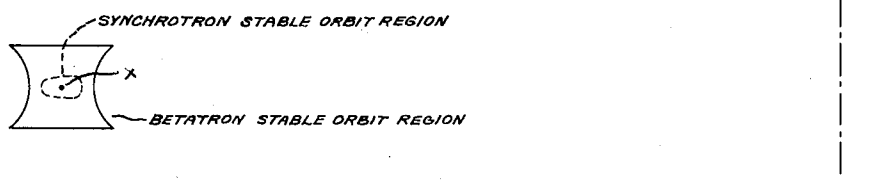


Fig. 4a.

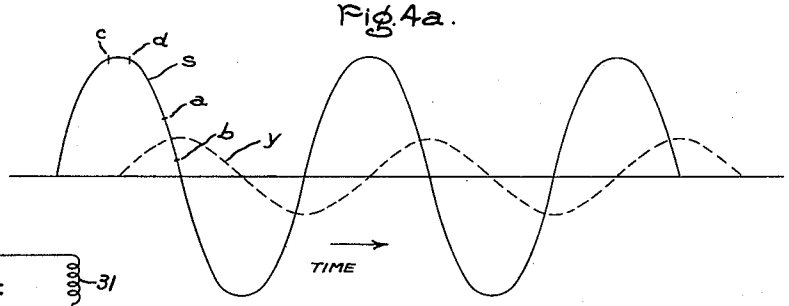


Fig. 5.

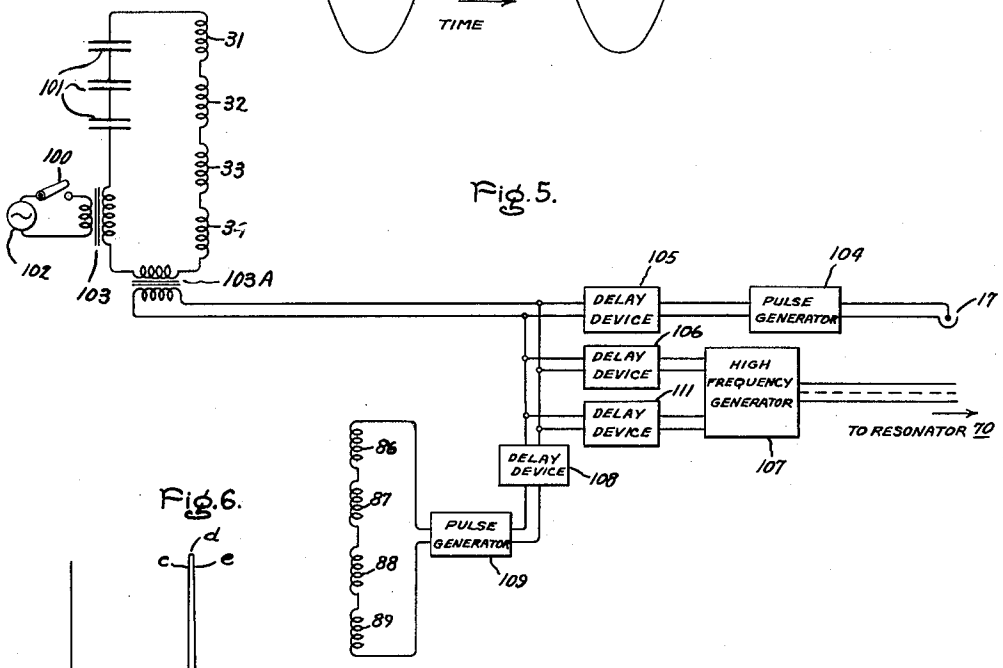
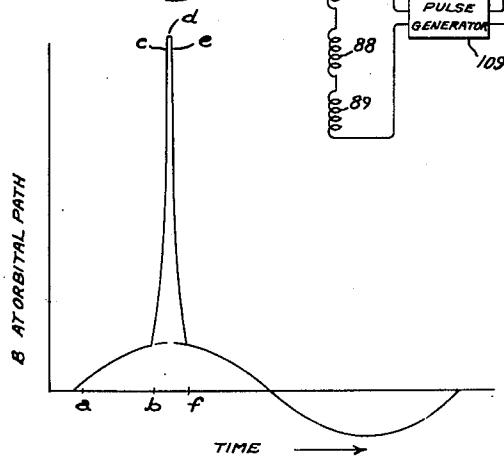


Fig. 6.



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APPARATUS FOR ACCELERATING CHARGED PARTICLES

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Application November 18, 1950, Serial No. 196,482

11 Claims. (Cl. 250—27)

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The present invention relates to apparatus for imparting high energy to charged particles, particularly electrons.

It is now well known that energy of the order of several million electron volts or higher may be imparted to charged particles such as electrons by accelerating the particles in a generally circular path or orbit with magnetic induction effects. For example, an apparatus for producing this result is disclosed in U. S. Patent 2,394,071, granted February 5, 1946, to Willem F. Westendorp and assigned to the assignee of this present invention. Such apparatus is commonly referred to in the art as a betatron and comprises field generating means for providing a time-varying magnetic flux which links the orbital path to accelerate the particles and a time-varying magnetic guide field which traverses the locus of the orbital path for constraining the particles thereto.

It is also known that further energy may be imparted to charged particles such as electrons by subjecting them to the repetitive action of a localized cyclically-varying electric field after they have been accelerated to a desired energy level by the above-mentioned betatron apparatus. Suitable apparatus for achieving this purpose is disclosed in U. S. Patent 2,485,409, granted October 18, 1949, to Herbert C. Pollock and Willem F. Westendorp and also assigned to the assignee of this invention. This latter apparatus may be referred to as synchrotron apparatus utilizing betatron start. It generally comprises means such as a high frequency resonator coupled to the charged particle orbital path for applying a localized cyclically-varying electric field to accelerate the particles after they have been preaccelerated by betatron action, and means for producing a time-varying magnetic guide field traversing the locus of the orbital path for constraining the particles thereto during the application of the electric field.

Both of the above-mentioned forms of apparatus for accelerating charged particles commonly employ an iron core for the production of the proper magnetic fields and fluxes. Because such an iron core must be laminated to minimize the generation of eddy currents and has great weight, fabrication and handling present major problems. Moreover, it is very difficult to eliminate azimuthal field asymmetries, and the limitations upon magnetic induction imposed by saturation of the iron necessitate large amounts of stored energy in the accelerator apparatus. As is disclosed in U. S. Patent 2,465,786 to John P. Blewett, the disadvantages represented by the

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iron core may be obviated by the expedient of producing the desired magnetic fields and fluxes with non-ferromagnetic field generating means.

In the construction of non-ferromagnetic synchrotron apparatus utilizing betratron start, it is desirable that the magnetic field and flux generating means should couple as closely as possible with the charged particle orbital path so that energy need not be stored in a greater volume of space than necessary. This is particularly desirable in connection with the magnetic guide field which is provided during the period of synchrotron acceleration, because the magnetic field intensity of magnetic induction required during that period to retain the charged particles within the orbital path is much greater than the magnetic field intensity required during the betratron start period. It is also desirable that the stable region, or the region surrounding the orbital particle path within which proper acceleration can occur, be as large as possible during the betatron start period in order to increase the total number of charged particles which may be accelerated, to reduce loss of charged particles due to scattering to the walls of the apparatus, and to render less serious the presence of small field inhomogeneities. During the subsequent period of acceleration, these latter undesirable effects are not excessively bothersome because, during the betatron start period, the amplitude of the charged particle oscillations about the stable orbital path decreases considerably.

In accordance with the present invention, there is provided improved non-ferromagnetic charged particle accelerating apparatus which comprises non-ferromagnetic field generating means enclosed by a metal tank adapted for internal evacuation. The field generating means includes two sets of windings, one of which provides the requisite time-varying magnetic flux and guide field for initially applying betatron acceleration to charged particles suitably introduced into the tank, and the other of which provides the time-varying magnetic guide field which is required during the subsequent period of synchrotron acceleration. This construction allows the placement of the synchrotron guide field windings in a region closely adjacent the stable orbital path whereby the energy stored in the synchrotron field may be minimized. Furthermore, since the betatron and synchrotron field generating means include separate windings, they may be separately energized thereby permitting the arrangement of a much slower rate of rise for the betatron field and flux to reduce eddy field disturbances and

the criticalness of the charged particle injection timing. Moreover, it is possible to make the betatron stable region much larger in order to increase the total number of charged particles which may be accelerated, to reduce loss of particles due to gas scattering, and to render less serious the presence of small field inhomogeneities.

Other objects and advantages of this invention will be apparent from the following description taken in connection with the accompanying drawings in which Fig. 1 is a sectionalized elevation of non-ferromagnetic synchroton apparatus suitably embodying the invention and taken along line 1—1 of Fig. 2; Fig. 2 is a sectionalized view taken along line 2—2 of Fig. 1; Figs. 3, 3*a*, 4 and 4*a* are graphical representations useful in explaining the invention; Fig. 5 is a schematic diagram showing exemplary circuit connections for energizing the apparatus of Figs. 1 and 2; and Fig. 6 is another graphical representation useful in explaining the invention.

Referring now to Figs. 1 and 2, there is shown non-ferromagnetic charged particle accelerating apparatus comprising an air-tight tank 1 which may be evacuated through a suitable connection 2 attached to the base plate 3 of tank 1. Base plate 3 and a cover plate 4 may be retained in air-tight relation with respect to a cylinder 5 by means of a plurality of peripherally spaced screws 6 inserted through circular gaskets 7, which may consist of a suitable synthetic rubber material. Base plate 3, cover plate 4, and cylinder 5, which define chamber 5', must be of sufficient thickness to withstand internal evacuation without serious deformation and, therefore, should consist of a high tensile strength material, such as steel or iron.

Supported from the base plate 3 by means of circular dielectric spacer members 8 and 9 is a liner 10, the function of which will be more fully described hereinafter. Liner 10 preferably consists of a highly conductive non-ferromagnetic material such as copper and comprises a base plate 11, a cover plate 12 and a hollow cylinder 13. Base plate 11 and cover plate 12 are attached to cylinder 13 by means of a plurality of peripherally spaced screws 14, and an orifice 15 is provided in base plate 11 to permit internal evacuation of liner 10 through connection 2. For the sake of symmetry, an orifice 15' is situated in cover plate 12.

In order to provide for the injection of charged particles such as electrons for acceleration within liner 10, there is shown a source assembly 16 which may comprise an electron gun 17 having a filamentary cathode (not shown) suitable for injecting, in response to intermittent energization, a burst of electrons into the stable particle orbit indicated at point x. Structural details for gun 17, which may be advantageously employed in connection with the present invention, are disclosed and claimed in U. S. Patent 2,499,192, granted February 28, 1950 to James M. Lafferty and assigned to the assignee of the present invention. Gun 17 may be supported within a hollow tube 18 of a low-conductivity, non-ferromagnetic material such as stainless steel and energized through conductors (not shown) insulatingly introduced through tube 18. A slot 18' is provided in the lower end of tube 18 to permit the egress of electrons from gun 17. Tube 18 is flared out-wardly at its upper end to receive in hermetic relationship an insulator 19 and is also hermetically sealed adjacent its upper end to a base member 20. An apertured plate 21 is held by means of screws 22 against a boss 23 upon insulator 19 to compress packing material 24, thereby assuring a vacuum-tight relationship. In order to permit adjustment of the position of gun 17 within liner 10, base member 20 is supported by a flexible bellows 25 which is sealed at its lower end to the outer surface of tank 1 by means of an apertured plate 26, a compressible gasket 27 and screws 28. The position of gun 17 is maintained by means of a stud 29 and nuts 30, the latter of which may be screwed up or down to adjust bellows 25. Several studs 29, along with nuts 30, may be located around the periphery of base member 20 to insure desired positioning of gun 17.

As has been mentioned heretofore, the present invention contemplates the initial betatron acceleration of injected charged particles with non-ferromagnetic field generating means capable of supplying both a time-varying magnetic flux which links the orbital path of the charged particles to impart acceleration thereto and a time-varying magnetic guide field which traverses the orbital path for the purpose of constraining the charged particles thereto. Accordingly, betatron windings 31, 32, 33 and 34 are shown positioned adjacent the orbital path indicated at point x. The pair of windings 32 and 33 have a diameter greater than orbital path x while the pair of windings 31 and 34 have a lesser diameter. These windings comprise a plurality of circular hollow tubes 35 through which a suitable coolant such as water may be circulated. Windings 31, 32, 33 and 34 are series-connected and energized through hollow tubular conductors 36 by a suitable source of voltage (not shown) such that the current through all the windings flows in the same direction for a purpose to be more fully described hereinafter. Conductors 36 are hermetically sealed within tank 1 by means of insulators 37, apertured plates 38, screws 39 and packing material 40. To prevent a conductive connection to line 10, conductors 36 are inserted therein through apertures 41. Windings 31, 32, 33 and 34 are respectively supported from base plate 11 of liner 10 by means of dielectric spacers 42, coil supports 43, 44, 45 and 45, cylindrically-shaped spacer members 47 and 48 and dielectric shimming members 49, 50, 51 and 52.

To assure the retention of proper positioning of field generating windings 31, 32, 33 and 34, as well as of other components of the accelerating apparatus, during operational periods when tremendous forces are exerted thereupon due to the magnetic fields and fluxes which are generated, various support members are provided. These members include dielectric spokes 53 which bear at their outer ends against flanged hollow cylindrical members 55. Outward radial thrust may be imparted to spokes 53 by means of spreaders 56. Spreaders 56 comprise lower beveled cylindrical dielectric blocks 57 having studs 58 extending therefrom. Upper dielectric cylindrical beveled blocks 59 are apertured to permit the extension therethrough of studs 58 and block members 57 and 59 may be drawn together to exert outward radial thrust against cylindrical members 55 by means of dielectric nuts 60 which threadably engage stud 58. Notched circular dielectric spacer 61 is provided, as shown, to assure proper separation of members 47 and 48. To exert radial thrust between cylinder 13 of liner 10 and flanged cylindrical members 62, cylindrical spacer members 63 and 64 are employed

in connection with spreader members **65**, which are similar to the above described spreader members **56** and comprise upper and lower blocks **66** and **67**, studs **68**, and nuts **69**.

The dielectric materials utilized to form the various above-mentioned supports must be able to withstand the tremendous forces which are exerted thereupon when the accelerating apparatus is in operation. Furthermore, the large bulk of material in the supports must have a relatively low vapor pressure to permit successful evacuation of tank **1** and liner **10**. It has been found that the cylindrical supports may be advantageously constructed by winding glass cloth, which has been impregnated with a suitable organic resin, around a steel mandrel having a desired shape. After the desired form has been obtained in this manner, the support may be cured and stripped from the mandrel in a manner well known to those skilled in the art. Subsequently, the support may be machined to the desired dimensions. A suitable organic resin may consist of diallyl phthalate and diethylene glycol maleate along with a polyvinyl formal resin obtained by the partial hydrolysis of polyvinyl acetate and the reaction of the partially hydrolized product with formaldehyde.

It will now appear that, if the betatron field and flux producing windings **31**—**34** are energized from a source of time-varying voltage in a manner to be more fully described hereinafter, acceleration in an orbital path of charged particles injected from gun **17** may be obtained, providing the well known betatron flux and field considerations are satisfied. The betatron relationships which must be met are as follows:

$$\Delta\phi = 2\pi r_0^2 B_0 \qquad (1)$$

where $\Delta\phi$ is the total change in flux linking the orbit from the time at which the magnetic induction B is zero, r_0 is the radius of the orbit, and B_0 is the magnetic induction at the orbit;

$$B = B_0\left(\frac{r_0}{r}\right)^n \qquad (2)$$

where n is an exponent having a value between 0 and 1, B is the magnetic induction at a position under consideration and r is the radius of such a position. Equation 1 represents the flux-field condition which must be complied with to secure successful acceleration, and Equation 2 represents a stability condition which must be fulfilled before the charged particles will execute stable oscillations in the vicinity of the orbital path. In order to satisfy Equation 1, which need be met only along the stable orbit x, with two windings outside and two windings inside stable orbit x as shown, it is necessary to have the current flowing in all the windings in the same direction, whereupon the flux linking the orbital path is then in the same direction from both inner and outer windings while the field traversing the orbital path from the inner windings is opposite that from the outer windings. With the proper ratio of the number of turns in the outer windings to the number of turns in the inner winding, Equation 1 can be fulfilled. Equation 2 requires a nearly uniform field which falls off in proportion to $1/r^n$ in the region adjacent orbital path x. In order to fulfill Equation 2, it is necessary to match the shape of the magnetic induction curves of inner windings **31** and **34** and outer windings **32** and **33** such that the net magnetic induction falls off at the proper rate with the radius in the orbital region. In Fig. 3, curves of magnetic induction B in the orbital plane versus radius r are shown for both inner windings **31** and **34** and outer windings **32** and **33**. It will be observed from Fig. 3 that the desired falling off of magnetic induction with radius to give a value of n lying between 0 and 1 may be obtained at or near the field maxima of both inner and outer windings. This is more clearly shown in Fig. 3*a* which may be considered as an enlarged view of the right hand portion of Fig. 3.

While it is known that the above stated Equations 1 and 2 both must be fulfilled to obtain betatron acceleration of the charged particles, it has proved to be impractical to calculate accurately the field configurations resulting from windings **31**—**34** because of the difficulty of considering the effect of the liner **10**. Liner **10**, which is employed for a purpose to be more fully described hereinafter, reduces the field at the orbit and the flux linking the orbit and also changes the phases of the field and flux with respect to the current in windings **31**—**34**. Consequently, the most effective procedure for locating windings **31**—**34** has been found to be the employment of various scale models of inner and outer windings whereby the magnetic induction may be measured in a manner well known to those skilled in the art with a magnetic pick-up coil. By successive approximations it is possible to arrive at a geometry which satisfies Equation 1 along orbital path x and also produces a satisfactory field variation in both radial and vertical directions over the desired stable region in the vicinity of the orbital path as required by Equation 2. After windings **31**—**34** have been installed within liner **10**, vertical adjustment to correct for field discrepancies may be obtained by means of shims **49**—**52**. With the above-described winding configuration, a stable region of considerable extent adjacent the orbital path may be obtained, the shape of such a region being indicated by the solid line representation of Fig. 4.

In the discussion of the production of desired time-varying magnetic fields within the apparatus of the invention, consideration must be given to the problem of their confinement. Externally generated magnetic fields, or ferromagnetic material or conducting material outside the apparatus, cannot be permitted to disturb the fields inside the apparatus, nor can the internally generated fields be permitted to disturb external equipment which is employed in conjunction with the apparatus. Any shielding means that is utilized, however, must not introduce nonlinearities which would prevent procurement of the desired time-varying fields within the apparatus, as would be the case if tank **1**, which preferably consists of a ferromagnetic conductive material such as iron, were alone employed. Liner **10**, which preferably consists of a nonferromagnetic conductive material such as copper, provides shielding of time-varying magnetic fields within tank **1** without introducing undesired non-linearities. The magnetic shielding action of liner **10** is accomplished by eddy or "image" currents which flow therein in a direction such as to oppose the time-varying fields which induce them; consequently the time-varying magnetic fields which would have existed exteriorly of liner **10** during operation of the accelerating apparatus are cancelled, and tank **1** is prevented from disturbing the internally generated time-varying fields. Liner **10** and tank **1** together then serve as effective shields for the

apparatus inasmuch as tank 1 will effectively shunt direct current magnetic fields which will not be affected by liner 10.

After the charged particles have been accelerated to the desired energy level by means of betatron flux and field producing windings 31—34, further energy may be imparted to the particles by means of a cyclically-varying electric field produced by a high frequency circuit including a resonator 70. Resonator 70 is of the open-circuited coaxial line type in which a portion of an electrostatic shield 71, whose general function will be more fully described hereinafter, serves as the outer conductor and a plurality of vertical conductors 72 serve as the inner conductor. Both electrostatic shield 71 and inner conductors 72 are constructed of a plurality of separate wires of a non-ferromagnetic conductive material such as copper depending from cover plate 12 of liner 10 as shown, the individual wires being secured together by means of a desired insulating organic resin, such as the above-mentioned diallyl phthalate and diethylene glycol maleate. This construction serves to minimize the generation of disturbing eddy currents when the accelerating apparatus is in operation. Within conductors 72 a similar plurality of conductors 73 are provided, which, along with conductors 72, may subtend an arc of about 60° adjacent orbital path x. Conductors 72 and 73 are bent outward at their upper ends and soldered at 74 to a circular plate 75 of a non-ferromagnetic conductive material such as copper which is secured, along with shield 71, to cover plate 12 by means of right angle circular clamping members 76 and bolts 77 constructed from a non-ferromagnetic conductive material such as copper. Arcuate dielectric member 78 is positioned within conductors 73 to provide rigidity for the conductor assembly comprising conductors 72 and 73. Each of the wires of shield 71 and each of the conductors 72 and 73 may be provided, respectively, with circumferential slots 79, 80 and 81 to interrupt continuous current paths for unwanted eddy currents.

It will now be observed that, if resonator 70 is excited with an energized concentric line 82 hermetically introduced through cover plate 4 by means of a vacuum-tight bushing 83 and inductively coupled into resonator 70 at 84, a cyclically-varying electric field will be produced between outer conductor 71 and inner conductor 72, such a field fringing out at the ends of resonator 70 to couple with the orbital path x. If this electric field is of the proper frequency, energy may be imparted to charged particles during each revolution within orbital path x. Assuming that the charged particles are electrons and have been accelerated to approximately the velocity of light within orbital path x by betatron flux and field generating windings 31—34, their approximate frequency f will be given by the following relation:

$$f=\frac{c}{2\pi r_0} \qquad (3)$$

where c represents the velocity of light. Consequently, the frequency of excitation of resonator 70 may be arranged at a constant value such that energy is imparted to the charged particles upon each revolution.

According to the present invention, conductors 72 are provided with extensions 85 extending downwardly and about the charged particle orbital path x while conductors 73 terminate vertical extension above the path as indicated. This provides an R. F. field-free region 85' throughout the circumferential extension of conductors 72 and 73, such field-free region serving to shield the charged particles from the R. F. fields within resonator 70 while they are within region 85'. Therefore, if the frequency of excitation of resonator 70 is equal to or a multiple of the frequency given in Equation 3 for electrons, energy may be imparted to the electrons as a function of the time at which they enter and leave resonator 70.

A better understanding of the manner in which energy or acceleration is imparted to electrons by resonator 70 may be had by reference to Fig. 4a wherein the solid curve, labeled s, represents the variation with time of the R. F. electric field produced by resonator 70. If an electron enters at point a and leaves at point b, it will receive an energy increase or acceleration because it entered at a higher positive value of electric field than at which it left. If an electron enters at point c and leaves at point d, it will receive essentially no energy increase because the value of the electric field is nearly constant over the peak. Therefore, a curve such as dotted curve y may be drawn to represent the effective energy gain or acceleration of the electrons by traversal of resonator 70. It will be seen that the energy received or given up by the electrons becomes a function of the "drift time" or the time spent within the field-free region 85'.

It will be realized that, during acceleration of charged particles such as electrons by the betatron flux and field generating windings 31—34 before resonator 70 is energized, no bunching occurs because acceleration is achieved by means of an electric field along orbital path x created by the changing betatron flux linking the path, such a field being essentially circumferentially constant at any given instant. As a consequence, when resonator 70 is energized, electrons enter resonator 70 when the electric field is negative as well as when it is positive. However, due to the "phase stability" principle announced by E. M. McMillan in the Physical Review, vol. 68, pp. 143–144 (1945), bunching occurs after resonator 70 is energized and, since a time-varying magnetic guide field to be described presently is employed to maintain the electrons within an orbital path, the bulk of the electrons are accelerated or receive an energy increase as they travel along orbital path x in a stable manner.

Of course, charged particles moving along orbital path x are affected by any electric field which couples thereto. In order to prevent deleterious results, therefore, it is necessary to shield the orbital path from unwanted electric fields, e. g. those resulting from the electric potentials upon the various windings within the accelerator apparatus and those derived from charges collecting upon parts of the apparatus (especially insulators). Electrostatic shield 71, described hereinbefore, acts to perform this function. Shield 71 may be constructed of hollow wires and water-cooled if excessive overheating is encountered. Slots 79, as well as slots 80 and 81, may not be necessary, providing the respective conductors lie within close limits in planes passing through the axis of the accelerator apparatus.

In order to provide a time-varying magnetic guide field to constrain the charged particles to orbital path x as energy is being imparted thereto by resonator 70 in accordance with the principles

hereinbefore discussed, windings 86, 87, 88 and 89 are disposed adjacent orbital path x within circumferential slots in cylindrical spacer members 47 and 48 as shown. Windings 86—89 may comprise a plurality of tubes 90 through which a suitable coolant such as water may be circulated and to which energy may be supplied through hermetically sealed conductors (not shown) introduced through tank 1 in a manner similar to conductors 36. The magnetic field provided by windings 86—89 must meet the requirements of Equation 2 in that the magnetic guide field within the region surrounding orbit x must have the desired inverse slope with increasing radius; but the flux generated by windings 86—89 need not meet the requirements of Equation 1 since, during the period of energization of windings 86—89, energy is imparted to the charged particles by means of resonator 70 and not by means of a time-varying magnetic flux linking the orbit, as is the case during betatron acceleration. To produce a field complying with Equation 2 alone, a more efficient field producing arrangement may be employed, viz. windings 86—89 may be connected in series to a suitable source of time-varying voltage (not shown) such that the current in the two inner windings 86 and 89 flows in the opposite direction to the current flowing in the two outer windings 87 and 88, the direction of current flow in the outer windings being the same as the current flow in betatron windings 86—89. This results in a greater guide field intensity for a given winding current because the fields are additive within the stable orbit region. The value of the exponent n in Equation 2 in this instance depends upon the relative vertical spacings of the outer windings 87 and 88 compared to the relative vertical spacings of the inner windings 86 and 89, and the desired value may be obtained with the outer windings slightly farther apart vertically than the inner windings. The cross-sectional area of the orbital stable region will have dependent dimensions, i. e. the vertical extent may be increased by moving the windings farther apart vertically (without altering relative vertical spacings) but the horizontal extent will be decreased simultaneously and vice versa. As a practical matter, the cross-sectional area is arranged in accordance with the above considerations to be approximately as indicated by the dotted curve of Fig. 4. Windings 86—89 are positioned as close as possible to orbital path x to secure a large field at the orbit for a given current and stored energy in the windings; however, they cannot be in too close proximity because, even though the amplitude of the charged particle oscillations has been damped during the betatron start period, the charged particles still undergo some oscillation about orbital path x. Moreover, even though the charged particles are electrons and have been accelerated to nearly the velocity of light during the betatron start period, there is a slight increase in radius of orbital path x as a result of relatively small velocity increase during synchrotron acceleration to high energy levels.

Referring now to the exemplary circuitary of Figs. 5 and 6, the following sequence of events takes place after switch 100 of Fig. 5 is closed. As will be observed, betatron flux and field generating windings 31—34, which may be series resonated with capacitors 101, are connected to be energized in series by a time-varying source of voltage, such as alternating current source 102 and transformer 103. Peaking transformer 103a has its primary winding connected in circuit with windings 31—34, as shown, so that it will produce a voltage pulse in ts secondary circuit as the current through windings 31—34 and the flux generated thereby goes through zero. In a few microseconds thereafter when the magnetic induction at the orbital path x has reached a value which causes charged particles of several kilovolts energy to be constrained thereto, such as the point a of Fig. 6 wherein the magnetic induction B in the orbital plane is plotted versus time, gun 17 is energized by means of pulse generator 104, the initiation of which is determined by delay device 105. The charged particles which are thus introduced into orbital path x are accelerated by the betatron flux and field generating windings 31—34 until they have reached a desired energy level, at which time delay device 106 causes high frequency generator 107 to energize resonator 70. Within close proximity thereto, delay device 108 causes pulse generator 109 to energize synchrotron guide field windings 86—89. This latter sequence may be arranged to occur at point b as indicated on Fig. 6. After the charged particles have been accelerated further or desired additional energy has been imparted thereto by synchrotron guide field windings 86—89 and resonator 70, delay device 111 may be rendered effective to deenergize high frequency generator 107 at point c whereby the charged particles spiral inwardly from orbital path x for impingement upon a suitable target (not shown). Alternatively, delay device 111 may be rendered operative after the magnetic induction peak d has been traversed, e. g. the point e on Fig. 6, whereby the charged particles spiral outwardly and may be directed to a suitable target 112 (Fig. 2) for the production of desired effects. If the charged particles are electrons, high energy X-rays may be generated in this manner and extracted from tank 1 through a circumferential groove 113 (Fig. 1) within cylindrical member 48, a slot 113′ in shield 71 (Fig. 2), and a port 114 (Fig. 2).

It will be understood by those well skilled in the art that various forms of delay devices, pulse generators, and high frequency generators may be employed to secure the above mentioned purposes. It will also be understood that windings 31—34 and capacitors 101 may be energized in parallel by means of source 102 and transformer 103, although the above described series connection is to be preferred because harmonics in supply voltage are filtered and short-circuits in windings 31—34 are current-limited.

What we claim as new and desire to secure by Letters Patent of the United States is:

1. Apparatus for accelerating charged particles comprising means providing a chamber within which charged particles may be accelerated along an orbital path; means for injecting said charged particles; a first set of windings within said chamber for accelerating said particles along said orbital path including an outer pair of windings axially spaced on opposite sides of a plane in which said orbit lies and an inner pair of windings axially spaced on opposite sides of said plane, the space enclosed by said windings being substantially free of ferromagnetic material; means for energizing said first set of windings including a source of time-varying voltage connected thereto; said windings being spatially interrelated such that energization thereof by said source of time-varying voltage produces coinci-

dentally both a time-varying magnetic flux which links said orbital path to initially accelerate said particles and a time-varying magnetic guide field which traverses said orbital path to constrain said particles thereto; a high frequency circuit coupled with said orbital path and operative to impart further energy to said particles after initial acceleration by said first set of windings; a second set of windings enclosing a space within said chamber which is substantially free of ferromagnetic material and including an outer pair of windings axially spaced on opposite sides of said plane in which said orbit lies and an inner pair of windings axially spaced on opposite sides of said plane; and a source of time-varying voltage connected to said second set of windings; said second set of windings being spatially interrelated such that energization thereof by said last-named source of time-varying voltage near the time said high frequency circuit becomes operative produces a time-varying magnetic guide field which constrains said particles to said orbital path during the imparting of further energy thereto by said high frequency circuit.

2. Apparatus for accelerating charged particles comprising means providing a chamber within which charged particles may be accelerated along an essentially circular path; means for injecting charged particles within said chamber; a first set of windings within said chamber for accelerating said charged particles along said path including two pairs of windings enclosing a space which is substantially free of ferromagnetic material, one of said pairs of windings having a diameter greater than said path and the other having a diameter less than said path, each winding in each pair being disposed on the opposite side of a plane in which said path lies in relation to the remaining winding of each respective pair; means for energizing said first set of windings including a source of time-varying voltage connected thereto; said windings being spatially interrelated and series-connected such that energization thereof by said source of time-varying voltage produces coincidentally both a time-varying magnetic flux which links said path to initially accelerate said particles and a time-varying magnetic guide field which traverses said path to constrain said particles thereto; a high frequency circuit including an electric field producing means coupled with said path and operative after a predetermined time to impart further energy to said particles following initial acceleration by said first set of windings; a second set of windings enclosing a space within said chamber which is substantially free of ferromagnetic material and including two pairs of windings, one of said pairs of windings having a diameter greater than said path and the other having a diameter less than said path, each winding in each pair being disposed on the opposite side of said plane in which said path lies in relation to the remaining winding of each respective pair; and a source of time-varying voltage connected to said second set of windings; said second set of windings being spatially interrelated and series-connected such that energization thereof by said last-named source of time-varying voltage near the time said high frequency circuit becomes operative produces a time-varying magnetic guide field which traverses said path and constrains said particles thereto during the imparting of further energy by said high frequency circuit.

3. Apparatus for accelerating charged particles comprising means providing a chamber within which charged particles may be accelerated along an orbital path; means for injecting charged particles within said chamber; betatron field and flux generating windings supported within said chamber and having a non-ferromagnetic core, said windings including one pair of substantially coaxial windings having a diameter greater than said orbital path and a second pair of substantially coaxial windings having a diameter less than said orbital path, each winding in each pair being disposed on the opposite side of a plane in which said orbital path lies in relation to the remaining winding of each respective pair; means for energizing said betatron windings including a source of time-varying voltage connected thereto; said windings being spatially interrelated such that energization thereof produces conditions coincidentally satisfying the two relations:

$$\Delta\phi = 2\pi r_0^2 B_0$$

where $\Delta\phi$ is the total change in flux linking the orbital path from the time at which the magnetic induction B is zero, r_0 is the radius of the orbital path, and B_0 is the magnetic induction at the orbital path; and

$$B = B_0\left(\frac{r_0}{r}\right)^n$$

where n is an exponent having a value between 0 and 1 and r is the radius of a position under consideration; the energization of said betatron windings being effective to produce initial acceleration of said injected charged particles along said orbital path to a desired energy level; a high frequency circuit including an electric field generating means coupled with said orbital path and operative following said initial acceleration by said betatron windings to impart additional energy to said charged particles; further windings supported within said chamber and having a non-ferromagnetic core, said further windings including one pair of substantially coaxial windings having a diameter greater than said orbital path and a second pair of substantially coaxial windings having a diameter less than said orbital path, each winding in each pair being disposed on the opposite side of a plane in which said orbital path lies in relation to the remaining winding of each respective pair; said further windings being spatially interrelated such that energization thereof by said last-named source of time-varying voltage near the time said high frequency circuit becomes operative produces a time-varying magnetic guide field which satisfies only the second of said two relations and constrains said particles to said orbital path during the imparting of further energy by said high frequency circuit.

4. Apparatus for accelerating charged particles comprising means providing a chamber within which charged particles may be accelerated along an orbital path, betatron field and flux generating windings magnetically coupled with said path, a source of time-varying voltage connected to said windings for energizing the same to produce coincidentally a time-varying magnetic flux which links said orbital path and a time-varying magnetic guide field which traverses said orbital path, means for projecting charged particles along said orbital path at a timed instant early in the cycle of energization of said betatron field and flux generating windings whereby said particles will be initially accelerated by said time-varying mag-

netic flux while being constrained to said orbital path by said time-varying magnetic guide field, synchrotron means for imparting further energy to said charged particles including a high frequency circuit having electric field producing means coupled with said orbital path, a source of high frequency voltage connected to said circuit for energizing the same at a timed instant later in the cycle of energization of said betatron field and flux generating windings whereby said particles will have further energy imparted thereto by said synchrotron means after initial acceleration by said betatron field and flux generating windings, synchrotron guide field windings magnetically coupled with said path, and a source of time-varying voltage connected to said last-named windings for energizing the same at a timed instant near the energization of said high frequency circuit to produce with said synchrotron windings a second magnetic guide field traversing said orbital path whereby said charged particles will be constrained to said orbital path during the imparting of additional energy thereto by said synchrotron means.

5. Apparatus for accelerating charged particles comprising means providing a chamber within which charged particles may be accelerated along an orbital path, betatron field and flux generating windings magnetically coupled with said path, a source of time-varying voltage connected to said windings for energizing the same to produce coincidentally a time-varying magnetic flux which links said orbital path and a time-varying magnetic guide field which traverses said orbital path, a source of charged particles, circuit means connected to said source for energizing the same at a timed instant early in the cycle of energization of said betatron field and flux generating windings whereby said particles will be initially accelerated by said time-varying magnetic flux while being constrained to said orbital path by said time-varying magnetic guide field, synchrotron means for imparting further energy to said charged particles including a high frequency circuit having electric field producing means coupled with said orbital path, a source of high frequency voltage and timing means connected to said high frequency circuit for energizing said high frequency circuit at a timed instant later in the cycle of energization of said betatron flux and field generating windings whereby said particles will have further energy imparted thereto by said synchrotron means after initial acceleration by said betatron field and flux generating windings, synchrotron guide field windings magnetically coupled with said path, a source of time-varying voltage connected to said synchrotron windings, and circuit means connected to said last-named source for energizing the same at a timed instant near the energization of said high frequency circuit to produce with said synchrotron windings a second magnetic guide field traversing said orbital path whereby said charged particles will be constrained to said orbital path during the imparting of additional energy thereto by said synchrotron means.

6. In apparatus for accelerating charged particles along an orbital path, an air-tight tank of ferromagnetic material enclosing said path, a plurality of windings insulatingly supported in spaced relationship within said tank, means for energizing said windings with time-varying current, and a liner of non-ferromagnetic material insulatingly supported within said tank and enclosing said windings for confining the time-varying magnetic fields and fluxes generated by said windings.

7. In apparatus for accelerating charged particles along an orbital path, an air-tight tank of ferromagnetic material enclosing said path, said tank being arranged to be evacuated, a plurality of windings insulatingly supported in spaced relation within said tank and enclosing a space substantially free of ferromagnetic material, means for energizing said windings with time-varying current, and a liner of non-ferromagnetic material insulatingly supported within said tank and enclosing said windings for confining the time-varying magnetic fields and fluxes generated by said windings.

8. In apparatus for accelerating charged particles along an orbital path, an air-tight tank of ferromagnetic material enclosing said path, a plurality of windings insulatingly supported in spaced relationship within said tank and defining among themselves an annular space within which said orbital path lies, means for energizing said windings with a time-varying current to provide a plurality of magnetic fields and fluxes within said tank, and an annular electrostatic shield supported within said tank and extending into said annular space defined by said windings to shield charged particles traveling along said path from the electric potentials on said windings.

9. In apparatus for accelerating charged particles along an orbital path, an air-tight tank of ferromagnetic material enclosing said path, a plurality of windings insulatingly supported in spaced relationship within said tank and defining among themselves an annular space within which said orbital path lies, said windings mutually enclosing a space substantially free of ferromagnetic material, means for energizing said windings with a time-varying current to provide a plurality of magnetic fields and fluxes within said tank, a liner of non-ferromagnetic material insulatingly supported within said tank and enclosing said windings for confining the time-varying magnetic fields and fluxes generated by said windings, and an electrostatic shield supported within said liner and extending into said annular space defined by said windings to shield charged particles traveling along said path from the electric potentials on said windings.

10. In apparatus for accelerating charged particles along an orbital path, an air-tight tank of ferromagnetic material enclosing said path, a plurality of windings insulatingly supported in spaced relationship within said tank and defining among themselves an annular space within which said orbital path lies, said windings mutually enclosing a space substantially free of ferromagnetic material, means for energizing said windings with a time-varying current to provide a plurality of magnetic fields and fluxes within said tank for accelerating charged particles along said path, a liner of non-ferromagnetic material insulatingly supported within said tank and enclosing said windings for confining the time-varying magnetic fields and fluxes generated by said windings, an electrostatic shield supported within said liner and extending into said annular space defined by said windings to shield charged particles traveling along said path from the electric potentials on said windings, said shield comprising a plurality of conductors depending from said liner and forming substantially an annular enclosure about said path, a plurality of conductors depending from said liner and extending into said annular enclosure formed by said shield,

said last-named plurality of conductors forming an enclosure about only a portion of said path, said first and second-named plurality of conductors forming the boundaries of a high frequency resonator, and means for exciting said resonator to generate an electric field for also accelerating charged particles along said path.

11. Apparatus for accelerating charged particles along an orbital path comprising a set of betatron field and flux generating windings positioned adjacent the orbital path for accelerating said particles along the orbital path to a predetermined energy level by betatron action, a high frequency circuit coupled with the orbital path to impart synchrotron acceleration to said particles following said betatron acceleration, and a set of synchrotron guide field windings positioned adjacent said orbital path for constraining said particles to said orbital path during the period of said synchrotron acceleration.

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