April 1, 1958 H. R. KRATZ 2,829,249

APPARATUS FOR ACCELERATING CHARGED PARTICLES

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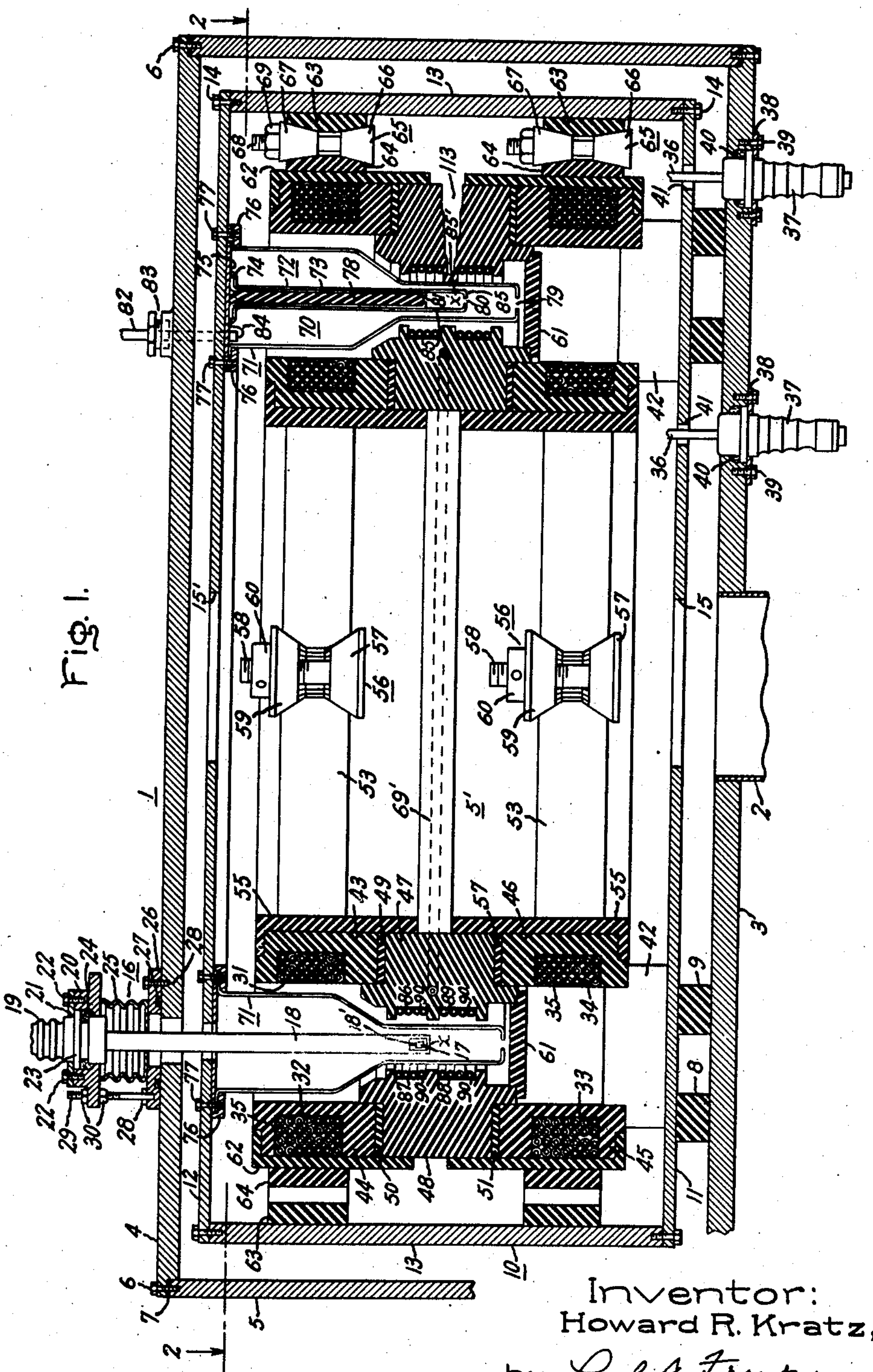

Fig. 1.

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Fig. 2.

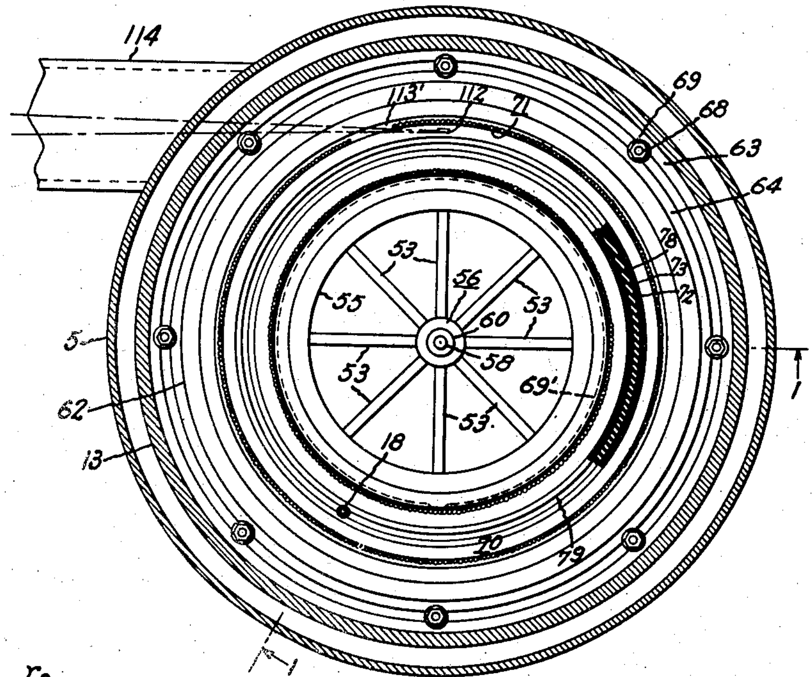

Fig. 3.

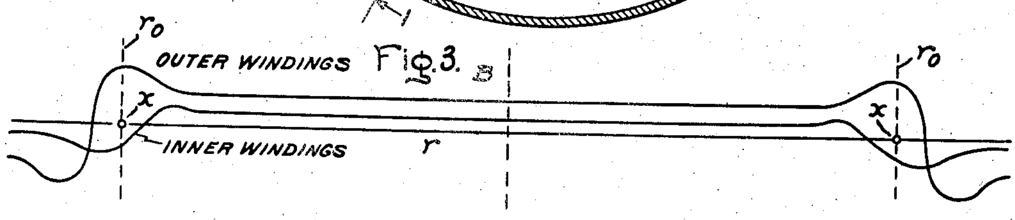

Fig. 3a.

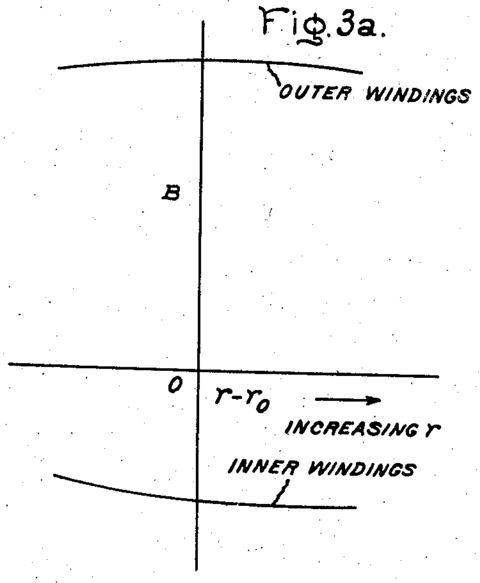

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Fig. 4.

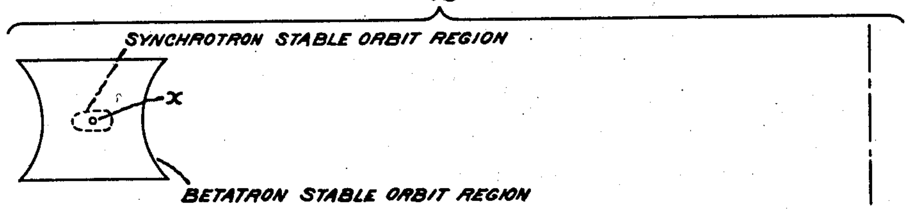


Fig. 5.

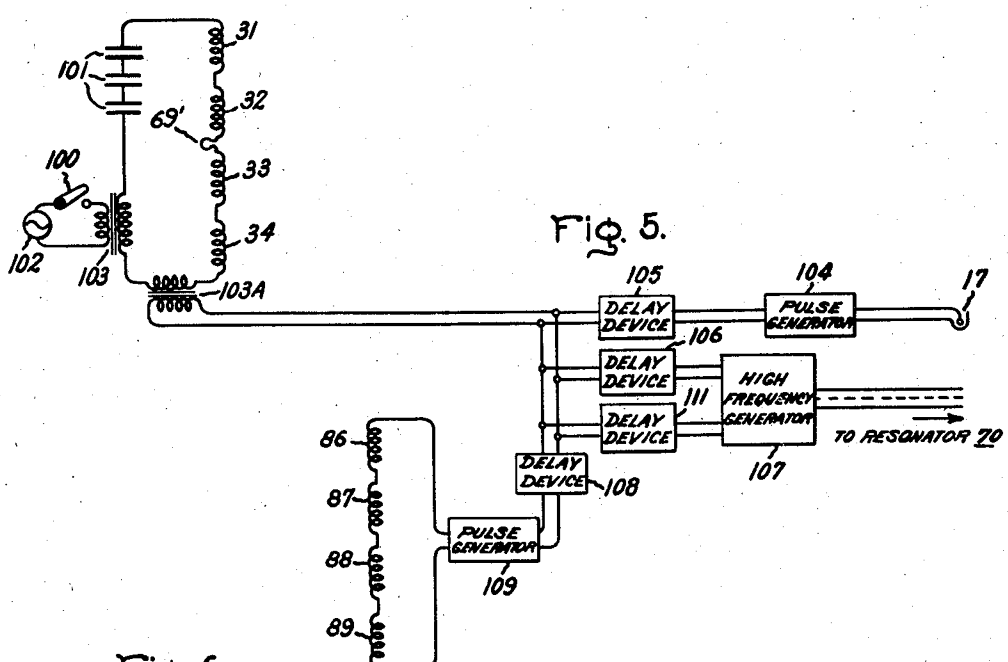
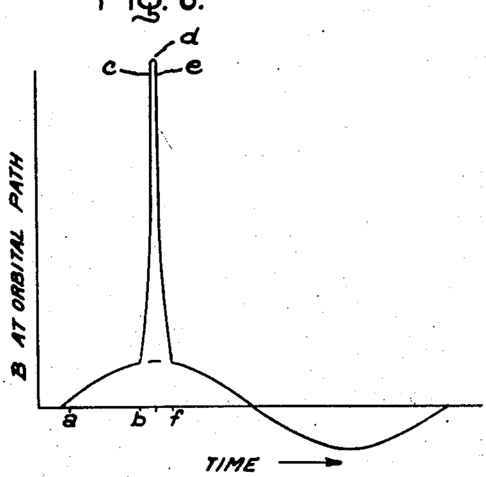


Fig. 6.



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APPARATUS FOR ACCELERATING CHARGED PARTICLES

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Application August 21, 1952, Serial No. 305,613
9 Claims. (Cl. 250—27)

The present invention relates to apparatus for imparting high energy to charged particles, particularly electrons. This invention relates particularly to and is an improvement over apparatus of the type disclosed in Patent 2,622,194, granted December 16, 1952, upon an application of James L. Lawson, Howard R. Kratz and George L. Ragan, Serial No. 196,482, filed November 18, 1950, and assigned to the assignee of the present application.

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, 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 the present invention. Such apparatus is commonly referred to in the art as a betatron, and it 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 can 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 pre-accelerated 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 forms of accelerator apparatus disclosed in the above-mentioned patents 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. The aforementioned Lawson et al. Patent 2,622,194 shows that the disadvantages represented by the iron core may be obviated by the expedient of producing the desired magnetic fields and fluxes with non-ferromagnetic field generating means.

In the aforementioned Patent 2,622,194 there is disclosed non-ferromagnetic charged particle accelerating apparatus which comprises non-ferromagnetic field generating means enclosed by a metal tank adapted for internal evacuation. Within the metal tank is disposed a non-ferromagnetic liner which has the same general shape as the tank and also encloses the field generating means. 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.

While the non-ferromagnetic synchrotron apparatus disclosed in Patent 2,622,194 has proved to be eminently satisfactory, it has been found that the set of betatron windings expends more power than is desirable. As shown and described in the aforesaid patent, the set of betatron windings comprises four individual coils or windings suitably coupled with the charged particle orbital path to produce the betatron field and flux. For obtaining a stable region surrounding the orbital path of sufficiently great cross-sectional area to permit fully successful acceleration of charged particles, it has been found necessary to locate the individual betatron windings farther from the orbital path than was anticipated. This has two undesirable effects: (1) the coupling to the orbital path is less, thus reducing the efficiency of the windings; and (2) the windings, being nearer the non-ferromagnetic liner, cause more power to be wastefully dissipated in the liner by currents generated therein.

It is a principal object of the present invention to provide a means for reducing the power consumption of non-ferromagnetic betatron field and flux generating windings.

According to one aspect of the present invention, there is provided improved non-ferromagnetic charged particle accelerating apparatus which comprises four betatron windings coupled with the charged particle orbital path for the purpose of supplying the requisite betatron field and flux. To reduce the power consumption of these windings for a given extent of the stable region of acceleration surrounding the orbital path, there is provided an auxiliary winding located in the plane of the orbital path. The auxiliary winding is energized such that it carries a current flowing in a predetermined direction with respect to the current in the remaining four betatron field and flux generating windings, whereby the net field of the four betatron windings is modified in a manner which permits their location more closely adjacent the orbital path for a given desired extent of the stable orbital region. Following initial acceleration of the charged particles with the five-winding geometry of the invention, synchrotron acceleration of the charged particles to higher energy levels can be accomplished, if desired, by the provision of synchrotron guide field windings and a cyclically-varying electric field coupled to the electric path.

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 synchrotron apparatus suitably embodying the invention and taken along line 1—1 of Fig. 2; Fig. 2 is a sectionalized view taken long line 2—2 of Fig. 1; Figs. 3, 3*a* and 4 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 according to the invention 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 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 charged particle orbital path 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 outwardly 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 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 liner **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 **46**, 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:

$$\Delta\phi = 2\pi r_o^2 B_o \qquad (1)$$

where $\Delta\phi$ is the total change in flux linking the orbit from the time at which the magnetic induction B is zero, r_o

is the radius of the orbit, and B_o is the magnetic induction at the orbit; and

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

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 along and 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 winding 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 along and 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**, **34** and outer windings **32**, **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 can be obtained at or near the field maxima of both inner and outer windings. This is more clearly shown in Figs. 3*a* which can be considered as an enlarged view of the right-hand portion of Fig. 3.

It has been found in practice, however, that the proper positioning of windings **31—34**, to secure a stable region surrounding the orbital path in accordance with Equation 2 of sufficient extent to permit fully successful acceleration of the charged particles, requires the location of these windings at relatively great distances from the orbital path. This reduces the coupling to the orbital path and hence reduces the efficiency of windings **31—34**. And since it is desirable to keep the dimensions of liner **10** as small as possible to reduce the volume which must be evacuated, the positioning of windings farther from the orbital path places them nearer liner **10**, thereby increasing wasteful power dissipation from eddy or "image" currents generated in the liner as a result of the time-varying currents flowing in the windings.

When the net magnetic induction of the windings **31—34** is plotted as a function of radius for various planes above and below the plane of the orbit, it is observed that the exponent n, which is proportional to the absolute magnitude of the slope of the magnetic induction versus radius curves, decreases in moving vertically (or in the "Z" direction parallel to the axis of the windings) from the orbital plane. It is this decrease in n that limits the vertical or Z direction extent of the stable orbital region. As the windings **31—34** are placed nearer the orbit, n decreases more rapidly and the stable region surrounding the orbit becomes smaller. According to the invention, this decrease in n in the vertical or Z direction is made less rapid by positioning an auxiliary winding **69'** in the plane of the orbital path as illustrated in Figs. 1 and 2. Winding **69'** has a radius smaller than that of the orbit and is connected, as will be more fully described hereinafter, in series with windings **31—34** so that it carries a current flowing in the same direction as the current in windings **31—34**. Although winding **69'** is shown as comprising only one turn, it can have additional turns depending upon the number of ampere-turns that are necessary to produce the desired compensation for the decrease in the n of the windings **31—34**.

The magnetic induction of winding **69'** alone, plotted as a function of radius for various planes above and below the orbital plane, results in curves which have decreasing absolute magnitudes of slope, or decreasing n values, at corresponding points farther away from the orbital plane. In other words, the field or magnetic induction of winding **69'** has a decreasing absolute magnitude of slope in the Z direction. The magnetic induction of winding **69'** is, however, in opposition to the net magnetic induction of windings **31—34** in the orbital plane; hence the n value of net magnetic induction of the entire combination of windings **31—34** and **69'** decreases more slowly with Z than does the magnetic induction of windings **31—34** alone. This is readily understood from the fact that the magnetic induction of winding **69'** decreases the n value of the net magnetic induction of windings **31—34** more in the orbital plane than above or below it. Since the n value of the entire combination of windings **31—34** and **69'** decreases more slowly with Z, it thus becomes possible to locate windings **31—34** nearer the orbit without decreasing the extent of the stable orbital region in the vertical or Z direction.

The utilization of auxiliary winding **69'** also affects the n value of windings **31—34** in the radial direction. The magnetic induction of winding **69'** decreases the value of n in the orbital plane, but this effect is more pronounced at radii smaller than the orbit since the n value of the magnetic induction of winding **69'** (which subtracts from the n of windings **31—34**) increases as the winding itself is approached. As the winding **69'** is approached from the orbit, the n value for the entire combination of windings **31—34**, **69'** actually decreases to zero and becomes negative. The radius at which n becomes zero is determined by the radius of winding **69'** and the magnitude of the magnetic induction from winding **69'** as compared with the magnetic induction from windings **31—34**. By a proper choice of the radius and number of turns of winding **69'**, the extent of the stable region can be extended to smaller radii without much affecting the radius outside the orbit at which the field becomes unstable. In this way the addition of winding **69'** can increase the total extent of the stable region in the radial direction as well as in the vertical or Z direction. Of course, the magnitude of the magnetic induction which can be supplied from winding **69'** is ultimately limited by its effect upon the magnetic induction outside the orbit.

Although it is preferred to position winding **69'** in the plane of the orbital path and with a radius smaller than the path, it can also be employed in the plane of the orbit with a radius larger than the path. In such event, the energization of winding **69'** can be by a series connection with windings **31—34**, but the current in winding **69'** must flow in a direction opposite to that in windings **31—34**. It is also contemplated that winding **69'** can comprise two sections in the orbital plane, one within and one outside the orbit. With the two sections connected in series with windings **31—34**, the current flow in the inner section must be in the same direction as the current in windings **31—34** and the current flow in the outer section must be in the opposite direction.

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 impractical to calculate accurately the field configurations resulting from windings **31—34** and **69'** because of the difficulty of considering the effect of liner **10**. Liner **10** is employed, in conjunction with tank **1**, as a shield for the field generating windings and for external apparatus. Liner **10**, however, 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, 69'. Consequently, the most effective procedure for locating windings 31—34, 69' has been found to be the employment of various scale models of inner, outer and auxiliary windings, whereby magnetic induction can be measured in a well known manner with a magnetic pickup coil connected to a voltage-responsive instrument. 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, 69' 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 relatively large extent adjacent the orbital path can be obtained, the shape of such a region being indicated by the solid line representation of Fig. 4.

After the charged particles have been accelerated to the desired energy level by means of betatron flux and field producing windings 31—34 and 69', further energy can 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 functions 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 form of 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:

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

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 a 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.

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 31—34 and 69'. 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 dimensons, 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 circuitry 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** and **69'**, 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 **103***a* has its primary winding connected in circuit with windings **31—34** and **69'**, as shown, so that it will produce a voltage pulse in its secondary circuit as the current through windings **31—34**, **69'** 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 net 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** and **69'** 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 from impingement upon a suitable target (not shown). Alternatively, delay device **111** can 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**, **69'** and capacitors **101** can 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**, **69'** are current-limited. From the foregoing description, it is apparent that windings **31—34** and **69'** can be advantageously employed without the associated synchrotron windings and circuitry for the purpose of accelerating charged particles to high energy levels by betatron effects alone. If it is found that the region surrounding the orbital path can not be evacuated sufficiently, electrostatic shield **71** in conjunction with the cover plate **4** of tank **1** can be formed into a separate hermetically sealed enclosure and evacuated by a separate pumping system.

While the invention has been described by reference to particular embodiments thereof, it will be understood that numerous changes can be made by those skilled in the art without actually departing from the invention. I therefore aim in the appended claims to cover all such equivalent variations as come within the true spirit and scope of the foregoing disclosure.

What I 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 can be accelerated along an orbital path; means for injecting said charged particles for acceleration within said chamber; a set of windings for accelerating said particles along said orbital path including an outer pair of windings having a diameter greater than said orbital path, an inner pair of windings having a diameter less than said orbital path and a winding positioned essentially in the plane of said orbital path adjacent and substantially non-coplanar to said inner and outer windings, said windings in said inner and outer pairs being connected together for current flow therethrough in the same direction, each winding in each of said inner and outer pairs of windings being disposed on the opposite side of the plane of said orbital path in relation to the remaining winding of each respective pair and all of said windings enclosing a space which is substantially free of ferromagnetic material; and means for simultaneously energizing all of said windings including a source of time-varying voltage connected thereto.

2. Apparatus for accelerating charged particles comprising means providing a chamber within which charged particles can be accelerated along an orbital path; means for injecting said charged particles for acceleration within said chamber; a set of windings for accelerating said particles along said orbital path including an outer pair of windings having a diameter greater than said orbital path, an inner pair of windings having a diameter less than said orbital path and a winding positioned essentially in the plane of said orbital path adjacent said inner and outer windings, said windings in said inner and outer pairs being connected together for current flow therethrough in the same direction, each winding in each of said inner and outer pairs of windings being disposed on the opposite side of the plane of said orbital path in relation to the remaining winding of each respective pair and all of said windings enclosing a space which is substantially free of ferromagnetic material; and electric conducting means connected to and interconnecting all of said windings for simultaneously supplying a time-varying voltage thereto to produce coincidentally both a time-varying magnetic flux which links said orbital path to accelerate said charged particles and a time-varying magnetic guide field which traverses said orbital path to constrain said particles to follow said orbital path within a relatively large radially and axially extending stable region surrounding said orbital path.

3. Apparatus as in claim 2 in which said winding positioned essentially in the plane of said orbital path has a diameter less than the diameter of said orbital path and is wound and connected relative to the remainder of said windings so that when energized it carries a current flowing in the same direction as the current in the remainder of said windings.

4. Apparatus as in claim 2 in which said winding positioned essentially in the plane of said orbital path has a diameter greater than the diameter of said orbital path and is wound and connected relative to the remainder of said windings so that when energized it carries a current

flowing in a direction opposite to that flowing in the remainder of said windings.

5. Apparatus as in claim 2 in which said winding positioned essentially in the plane of said orbital path includes two sections, one of said sections having a diameter greater than that of said orbital path and the other of said sections having a diameter less than that of said orbital path, said one section being wound and connected relative to the remainder of said windings so that when energized it carries a current flowing in a direction opposite to that flowing in the remainder of said windings and said other section being wound and connected relative to the remainder of said windings so that when energized it carries a current flowing in the same direction as that flowing in the remainder of said windings.

6. In non-ferromagnetic accelerating apparatus wherein charged particles are accelerated along an orbital path by means of a set of non-ferromagnetic cored windings connected together for current flow in the same direction to supply a time-varying magnetic flux that links the orbital path to accelerate the charged particles and a time-varying magnetic guide field that traverses the orbital path to constrain the particles thereto, the improvement which comprises means for increasing the stable region within which charged particles can be accelerated along the orbital path including a non-ferromagnetic cored winding positioned essentially in the plane of the orbital path and connected for simultaneous energization with said set of windings to supply magnetic flux and field supplementary to the magnetic flux and field supplied by the set of windings.

7. In non-ferromagnetic accelerating apparatus wherein charged particles are accelerated along an orbital path by means of a set of non-ferromagnetic cored windings connected together for current flow in the same direction to supply a time-varying magnetic flux that links the orbital path to accelerate the charged particles and a time-varying magnetic guide field that traverses the orbital path to constrain the particles thereto, the improvement which comprises means for increasing the stable region within which charged particles can be accelerated along the orbital path including a non-ferromagnetic cored winding positioned essentially in the plane of the orbital path and connected in series with the set of windings to supply magnetic flux and field supplementary to the magnetic flux and field supplied by the set of windings.

8. In a non-ferromagnetic synchrotron having a set of betatron windings connected together for current flow in the same direction for initially accelerating charged particles along an orbital path and electric-field producing means for continuing the charged particle acceleration, the improvement which comprises means for increasing the stable region within which charged particles can be accelerated along the orbital path including a non-ferromagnetic cored winding positioned essentially in the plane of the orbital path and connected for simultaneous energization with said betatron windings to supply magnetic flux and field supplementary to the magnetic flux and field supplied by the set of betatron windings.

9. In a non-ferromagnetic synchrotron, a set of betatron windings connected together for current flow in the same direction for initially accelerating charged particles along an orbital path, an electric field producing means including a set of synchrotron windings for continuing the charged particle acceleration constrained within said orbital path, and means for increasing the stable region within which charged particles can be accelerated along the orbital path including a non-ferromagnetic cored winding positioned essentially in the plane of the orbital path and connected for simultaneous energization with said betatron windings to supply magnetic flux and fields supplementary to the magnetic flux and fields supplied by said betatron windings.

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