Nov. 7, 1950 R. V. LANGMUIR ET AL 2,528,525

ELECTRON ACCELERATOR PROVIDED WITH STARTING AUXILIARY

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Fig. 1.

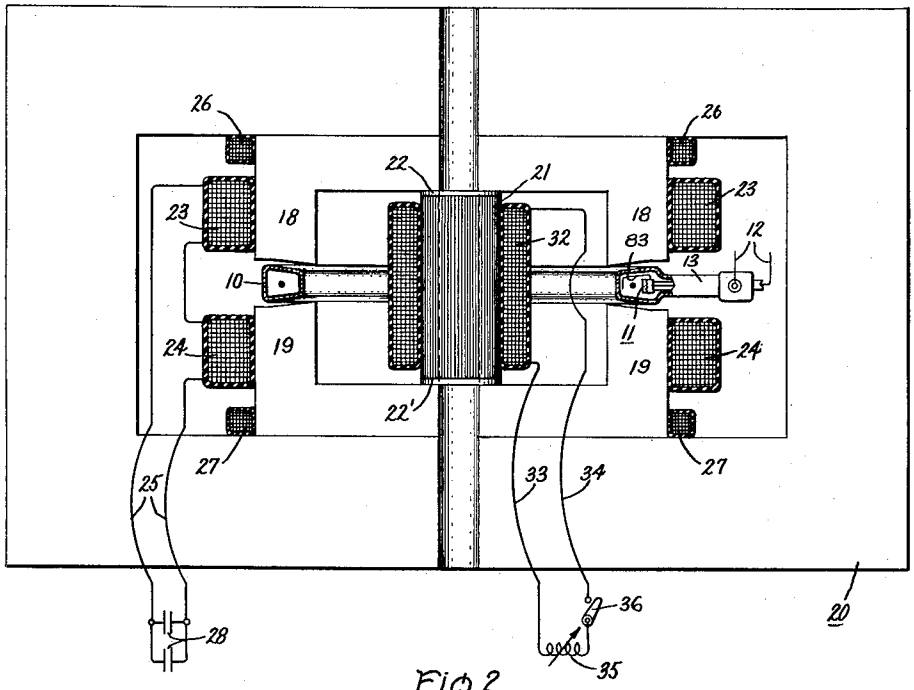
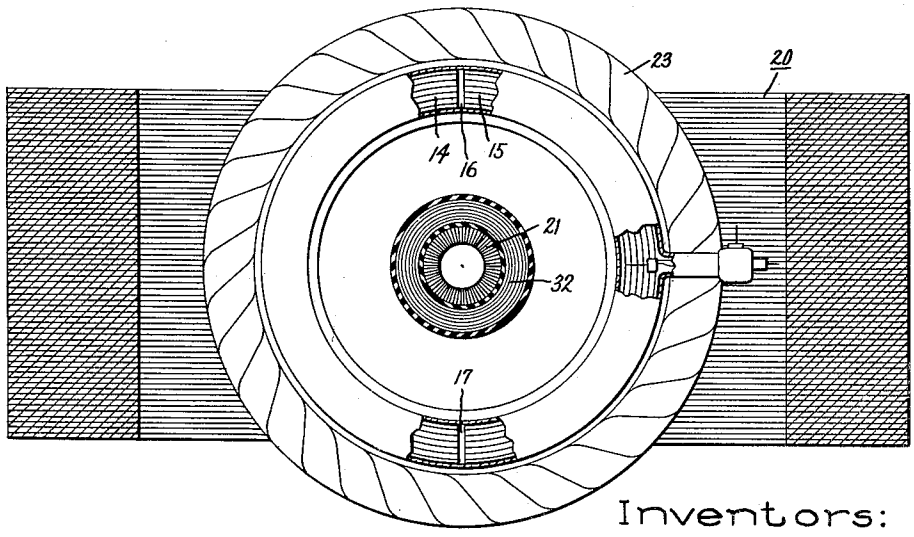


Fig. 2.



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Fig. 3.

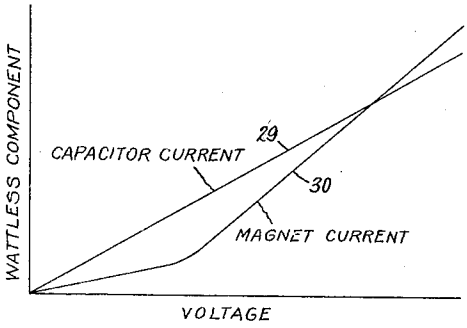


Fig. 4.

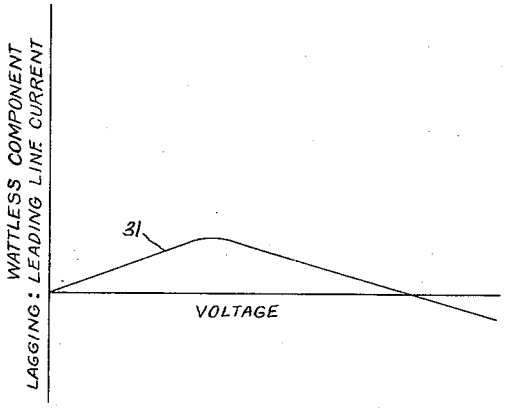
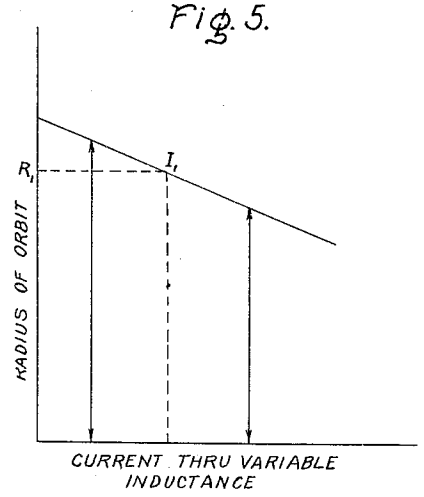


Fig. 5.



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Fig. 6.

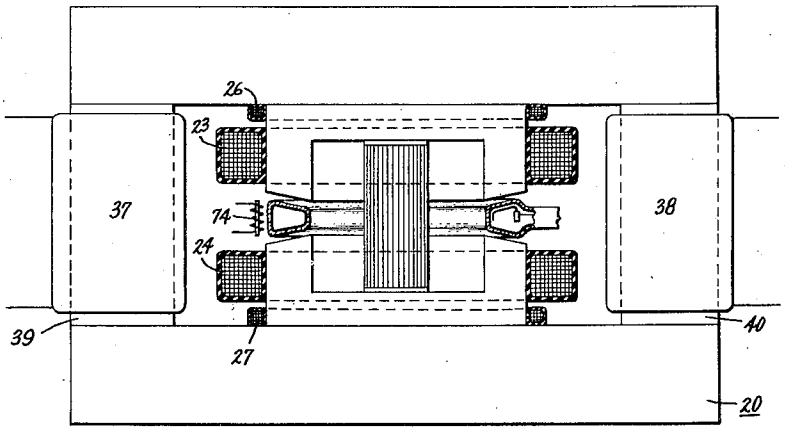
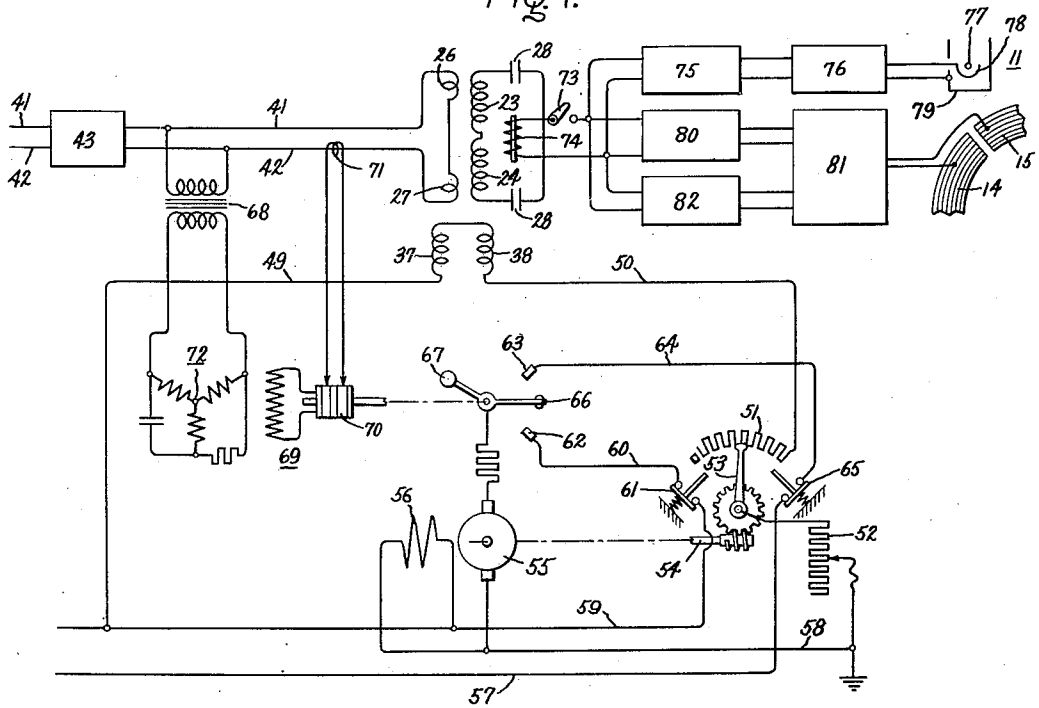


Fig. 7.



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UNITED STATES PATENT OFFICE

2,528,525

ELECTRON ACCELERATOR PROVIDED WITH STARTING AUXILIARY

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Application May 22, 1947, Serial No. 749,852

6 Claims. (Cl. 250—27)

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The present invention relates to apparatus for accelerating charged particles, and it is particularly directed to the provision of means for controlling the magnetic flux in such apparatus.

An apparatus in which charged particles are accelerated by a time-varying magnetic flux is commonly known as a "Betatron." The operation of betatron apparatus is described in Journal of Applied Physics, volume 16 (1945). An apparatus whereby charged particles are accelerated successively by an electric field is commonly known as a "Synchrotron." Its operation is described by E. M. McMillan in the Physical Review, volume 68, page 143.

A prior application, Serial No. 639,462, filed January 5, 1946 by Herbert C. Pollock and Willem F. Westendorp, which is assigned to the same assignee as the present application and has now issued as Patent No. 2,485,409, describes apparatus whereby charged particles are caused to be accelerated in an orbital path by cyclically varying magnetic and electric fields operating in succession. The initial acceleration of the charged particles is caused by a time-varying magnetic flux. When the charged particles have been accelerated to a predetermined velocity by the magnetic flux, they are additionally accelerated by a cyclic electric field which acts upon the gyrating particles at selected portions of their orbital path.

The present invention is applicable both to apparatus in which the acceleration of charged particles may be carried out wholly by a magnetic field, as described, for example, in Westendorp U. S. Patent 2,394,071, patented February 5, 1946 and to apparatus such as is described in the above-mentioned Pollock and Westendorp application in which magnetic and electric fields successively function to cause acceleration.

In a betatron such as described in the aforementioned Westendorp patent, the magnetic accelerating flux is generated in a magnetic core which is provided with one or more windings, arranged to be energized by alternating current. In circuit with the winding or windings is provided sufficient electric capacity to result in resonance at the operating frequency of the apparatus. During normal operation of a betatron, the excitation of the resonant electron-driving circuit occurs with but little power required to be supplied from an external source. In a properly designed system only about one per cent, or even less, of the circulating power in such resonant circuit represents a loss which must be compensated for by a supply of power.

In an accelerator in which acceleration of particles occurs solely by a time-varying magnetic field, ordinarily little difficulty is experienced in starting such apparatus, as all circuit elements are linear.

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However, apparatus providing for acceleration of electrons by a synchronous electric field subsequent to their acceleration by a varying magnetic flux is provided with a smaller central core which saturates early in the cycle of the magnetic field and remains saturated until the magnetic field returns to a value near zero $1/120$ of a second later for 60 cycle operation. When the accelerator is started the inductance and capacity of circuit containing the magnet windings are so far from resonance that excessive current would be drawn from the power lines if it were attempted to start the apparatus at normal operating frequency. No voltage will build up unless line currents many times greater than needed for full voltage steady state operation can be furnished.

In accordance with our present invention this difficulty is overcome by providing separate magnetic means for suitably regulating the effective tuning inductance of the electron-driving magnet as may be required to produce a condition of resonance with the associated capacitors at starting. In accordance with one of the embodiments of our invention a supplemental winding is provided on the central core of an accelerator. In circuit with this winding is provided a variable inductance device whereby the magnetic flux may be varied and desired resonance can be produced at will by suitable regulation with minimum line current going into the system.

In accordance with another feature of our invention, the regulable inductance device in circuit with a supplemental winding on the core of the accelerator is utilized during normal operation of an accelerator (i. e. subsequent to starting) for determining the orbit radius of the accelerated charged particles. It is desirable in a combination betatron-synchrotron device, such as described in the abovementioned Pollock and Westendorp application Ser. No. 639,462, that the orbit diameter at the close of betatron operation should match within about 1% the orbit diameter required for synchrotron operation. If a substantial difference should exist the electrons will be out of phase with the radio frequency accelerating electric field. The means provided by our invention of tuning the magnetic flux of the magnet core of the accelerator is operable for controlling the radius of the orbit of the gyrating particles while the accelerator is in operation.

Hence, it provides a means for adjusting the acceleration orbit for maximum power output.

These and other features of our invention will be described more fully in connection with the accompanying drawings, in which Fig. 1 is vertical section of an accelerator which is provided with an alternating current flux regulator; Fig. 2 is a top view of the accelerator shown partly in section; Figs. 3 and 4 are graphs of current-voltage relations; Fig. 5 is a diagram illustrating the relation of the orbit radius to the regulator current; Fig. 6 is a vertical section of an accelerator which is provided with a flux regulator operated by direct current excitation and Fig. 7 is a diagram of an operating circuit for an accelerator which is provided with a direct current flux regulator.

In Figs. 1 and 2 is shown a sealed, rotationally symmetric container 10, which provides an annular path for the acceleration of the charged particles. Ordinarily it consists of glass. Electrons are provided by an electron gun 11, the energizing conductors 12 of which are sealed into a side arm 13. As our present invention is not concerned with the construction of the electron gun and as the electron gun is described in prior patents and other publications, it will not be herein described. The container 10 is highly evacuated and as shown in Fig. 2, is provided on its interior surface with coatings 14, 15 of silver or other suitable conductive material which are separated by gaps 16, 17. The function of the electrodes which are longitudinally subdivided adjacent the gaps, as indicated, will be described hereinafter.

The acceleration chamber 10 is supported between the pole pieces 18, 19 of a rectangular magnetic frame 20 having a centrally located magnetic member 21, traversing the axis of the annular chamber 10, and being spaced from the main core structure by insulating spacers 22, 22'. The core member 21 as shown in Fig. 2, has a radially laminated structure. The core members 18, 19 consist also of radially placed laminations of various radial dimensions. The windings 23, 24 mounted on the pole pieces 18, 19 are connected in series by the conductors 25. The windings 23, 24 receive energy as secondaries from the primary windings 26, 27 which are energized from a source of alternating current (not shown). Capacitors of suitable size and number, symbolically indicated at 28, are provided in the circuit 25 to resonate at a frequency corresponding to the desired operating frequency of the apparatus, for example, at 60 cycles per second.

When the apparatus is started, and before the core member 21 is magnetically saturated, the windings 23, 24 and the capacitors 28 resonate at a frequency differing from the normal operating frequency. The apparatus hence would draw an excessive starting current from the supply source as illustrated by the graphs of Figs. 3 and 4. The wattless component of the capacitor current, graph 29, would vary with the voltage at a different rate than the wattless component of the inductive part of the load, graph 30. The graph 30 shows the wattless component at different voltages of the combined wattless ampere turns of coils 26, 23, 24 and 27 divided by the number of turns of coils 23 plus 24. The resultant wattless current in the circuit of the windings 26, 27 which would be obtained at different voltages is indicated by the group 31 of Fig. 4. The preponderance of capacity in the system initially would cause a large leading wattless current to flow. As the core saturates with rising applied voltage, the wattless component would become lagging as indicated by the graph 31 passing through zero. The actual power loss current, or watt component, is too small to be indicated on the scale of Fig. 4.

The difficulty described is avoided in accordance with our invention by providing a winding 32 on the core member 21 and connecting this winding by the conductors 33, 34 to a variable inductance device, which is conventionally indicated at 35. When the circuit is closed by the switch 36, the magnetic flux in the core member may be varied by suitable regulation of the inductance device 35 to establish and maintain a desired state of resonance in the circuit 25 until the accelerator is fully energized. The switch 36 then may be opened.

During normal operation of the accelerator the electron beam preferably should be in the center of the evacuated acceleration chamber as indicated by the dot in the center of the chamber 10, Fig. 1. The fulfillment of this condition depends on the relation between the flux density at the orbit and the flux through the orbit during the induction acceleration or betatron phase of the acceleration cycle, as expressed by the formula

$$2\pi R_0^2 \times B_0 = \phi_0$$

By changing the flux ϕ_0 in this relationship, the radius R_0 assumed by the electrons (orbit radius) can be adjusted at will. The flux can be varied by means of the current in the circuit of the coil 32. This current can be varied by adjusting the inductance 35. An adjustable resistance in this circuit would not result in the proper variation of current with time.

Fig. 5 shows the relationship between orbit radius and the current through the variable inductance. If the orbit is to be maintained at a value R_1 the current should be adjusted to a value I_1. Since the current flowing through the coil 32 and the inductance suppresses the flux in the central core member 21, the radius will decrease as the current in the winding 32 increases as shown in Fig. 5.

The shift from magnetic to synchronous high frequency field acceleration may be made automatic as will be described in connection with Fig. 7. It shows a system whereby the effective inductance of the magnetizing circuit is energized by unidirectional current controlled by a regulator. The latter system is described and claimed in a co-pending application, Serial No. 749,853, filed concurrently herewith by Willem F. Westendorp.

As shown in Fig. 6 the magnetic core 20 in this modification is partially excited by direct current windings 37, 38 which are located on the outermost legs 39, 40 of the magnetic core 20. The coils 37, 38 are connected to a source of direct current in series with a regulating resistance as shown in Fig. 7. Alternating current voltages which are induced in them neutralize one another and do not appear across the direct current supply. By an automatic device, which will be described in connection with Fig. 7, the direct current excitation is reduced as the excitation of the magnetization of the core 20 builds up until finally when the alternating current excitation is normal, no direct current remains in the windings 37, 38.

In the diagram of electrical connections, Fig. 7,

alternating current excitation is supplied by a source (not shown) through an input circuit 41, 42 in series with a voltage regulator 43 to the primary windings 26, 27 which are inductively related to the secondary windings 23, 24. The latter are connected in series with one another and in series with the capacitors 28. The windings 37, 38 as previously stated, are excited by direct current which here is shown as being supplied by the conductors 49, 50. The latter are connected to a source of direct current, represented by the supply conductors, 57, 58 and 59, in series with a regulable ohmic resistance 51 and a second series resistance 52. Although capable of being adjustable, as shown, the resistance 52 ordinarily is not varied during normal operation. The regulable resistor switch blade 53 is geared to the shaft 54 of the rotor 55 of a direct current motor. The field winding 56 of this motor is connected to the conductor 59 and to the grounded conductor 58 of a three-wire direct current supply system. Conductor 59 of this supply system is connected by a conductor 60, in series with a limit switch 61 to a stationary contact 62. A second stationary contact 63 is connected by a conductor 64 in series with a limit switch 65 to the direct current conductor 57.

When the apparatus is deenergized, a movable switch blade 66 is caused by the weight 67 to make contact with contact 63, causing the motor 55 to move the blade 66 to the right, thereby reducing the resistance of the circuit. When the apparatus is started maximum exciting direct current thus is supplied to the windings 37, 38. By the direct current excitation of windings 37, 38 a desired condition of resonance is established in the circuit containing the windings 23, 24. As the exciting alternating voltage is increased by the voltage regulator 43, the excitation of the stationary member 72 of a Selsyn which is energized by a transformer 68, the primary winding of which is connected across the circuit 41, 42 is increased. The movable member 69 of the Selsyn is connected by slip rings 70 to a current transformer 71 which is energized from the circuit 41, 42 as indicated. As excitation builds up in the magnet 20 and the circuit of the windings 23, 24 approximates a state of resonance the movable member of the Selsyn device first opens the contact 63 and thereupon causes the switch arms 66 to close the contact 62. This change in connections energizes the armature 55 to rotate in a reverse direction and insert resistance 51 into the direct current excitation circuit 49, 50 of the windings 37, 38. The excitation of the windings 37, 38 thus is decreased and eventually these windings are deenergized by the circuit 50 being opened.

Although the present invention is not concerned with the starting and operating circuits, such circuits are indicated conventionally in Fig. 7. As described in Westendorp U. S. Patent 2,394,071, the magnetic peaking strip 74 changes cyclically and abruptly from a saturated to an unsaturated condition in accordance with the variation of magnetic field and thereby controls the injection of electrons. When the switch 73 is closed, the variation of current in the winding of the peaking strip 74 through the intermediary of a control device 75 energizes a pulse generator 76 which feeds an electron gun 11 (Figs. 1 and 6) whereby electrons are introduced into the time-varying magnetic field generated by the windings 21, 22. As conventionally indicated in Fig. 7, the electron gun comprises a thermionic filament 77, a focussing cup 78 and a housing 79. After a predetermined time interval during which the electrons are accelerated solely by a magnetic field, a delayed action switching device 80 connects a high frequency source 81 to the electrodes 14, 15 on the interior of the accelerator chamber, as diagrammatically indicated in Fig. 7.

After a predetermined period of acceleration a second electronic delay device 82 effects a discharge of the accelerated electrons for example upon a target 83 (Fig. 1), as is well understood.

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

1. In an accelerator for charged particles which is provided with a magnetic core and magnetizing circuit therefor containing capacitors for impressing a time-varying magnetic field on said particles the improvement which consists in the combination of a winding surrounding said core, and only a variable inductance connected to said winding in closed circuit therewith.

2. In apparatus for accelerating charged particles in an orbital path the combination of a loop-shaped magnetic core having a magnetic member extending across said loop and traversing the area enclosed by the orbital path, magnetizing windings for said core, a capacity circuit coupled with said windings, an auxiliary winding on said transverse magnetic member, and a regulable inductance device external to said accelerator and in circuit with said auxiliary winding.

3. An electron accelerator comprising the combination of an annular evacuated container providing an orbit for the acceleration of electrons, means for introducing electrons into said orbit, a magnetic core having pole pieces respectively adjacent to and on opposite sides of said container and also having a magnetic member traversing the axis of said container, said axial member being magnetically saturated during normal operation of said accelerator, magnetizing primary windings on said pole pieces, secondary windings inductively related thereto, electric capacitors connected to said secondary windings to provide a circuit, inductance and capacity proportioned to be resonant at a predetermined frequency under operating conditions but being non-resonant under starting conditions, a magnetic winding on said axial member and a regulable inductance device connected to said winding and being located external to said accelerator whereby said circuit may be tuned to permit said accelerator to be started.

4. In magnetic induction apparatus for accelerating charged particles in an orbital path, said apparatus having a rotationally symmetrical magnetic core and magnetizing windings for impressing upon said particles a time-varying magnetic flux which links said orbital path to accelerate said particles and a time-varying magnetic field which constrains said particles to said orbital path, said magnetizing windings having sufficient capacitance in circuit therewith to be resonant under operating conditions of voltage and frequency, the improvement which comprises auxiliary rotationally symmetrical windings on said core energized by inductive coupling thereto and having in circuit therewith means for regulating the alternating current flowing in said latter windings whereby said time-varying flux linking said orbital path may be altered.

5. In magnetic induction apparatus for accelerating charged particles in an orbital path, said apparatus having a rotationally symmetrical magnetic core and magnetizing windings for im-

pressing upon said particles a time-varying magnetic flux which links said orbital path to accelerate said particles and a time-varying magnetic field which constrains said particles to said orbital path, said magnetizing windings having sufficient capacitance in circuit therewith to be resonant under operating conditions of voltage and frequency, the improvement which comprises additional windings on said core energized by inductive coupling thereto, said additional windings having electrically connected thereto only a dissipative circuit capable of regulating the alternating current flowing in said additional windings whereby said time-varying flux linking said orbital path may be altered.

6. In an accelerator for charged particles which is provided with a magnetic core and magnetizing circuit therefor containing capacitors for impressing upon said particles a time-varying magnetic field which links said orbital path to accelerate said particles and a time-varying magnetic field which constrains said particles to said orbital path, said magnetizing windings having sufficient capacitance in circuit therewith to be resonant under operating conditions of voltage and frequency, the improvement which comprises additional windings on said core energized by inductive coupling thereto, said additional windings having electrically connected thereto only a dissipative circuit capable of regulating the alternating current flowing in said additional windings whereby said time-varying flux linking said orbital path may be altered.

pressing a time-varying magnetic field on said particles, the improvement which comprises the combination of a winding surrounding said core and only a variable inductance and a switch connected to said winding in series circuit therewith.

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WILLEM F. WESTENDORP.

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