Jan. 6, 1953 E. M. McMILLAN 2,624,841

METHOD OF AND APPARATUS FOR ACCELERATING TO HIGH ENERGY ELECTRICALLY CHARGED PARTICLES

Filed May 3, 1946 3 Sheets-Sheet 1

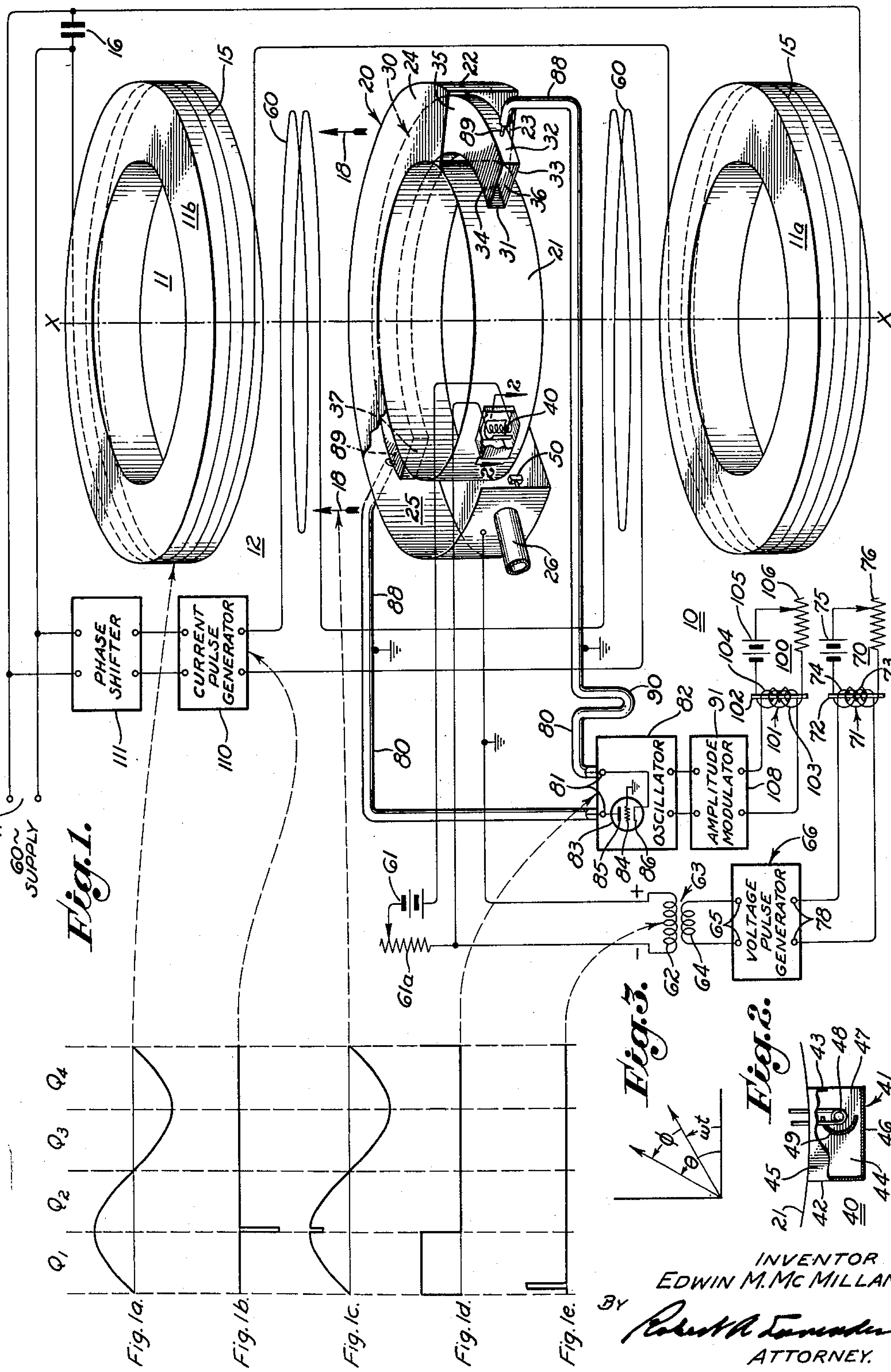

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Fig. 4.

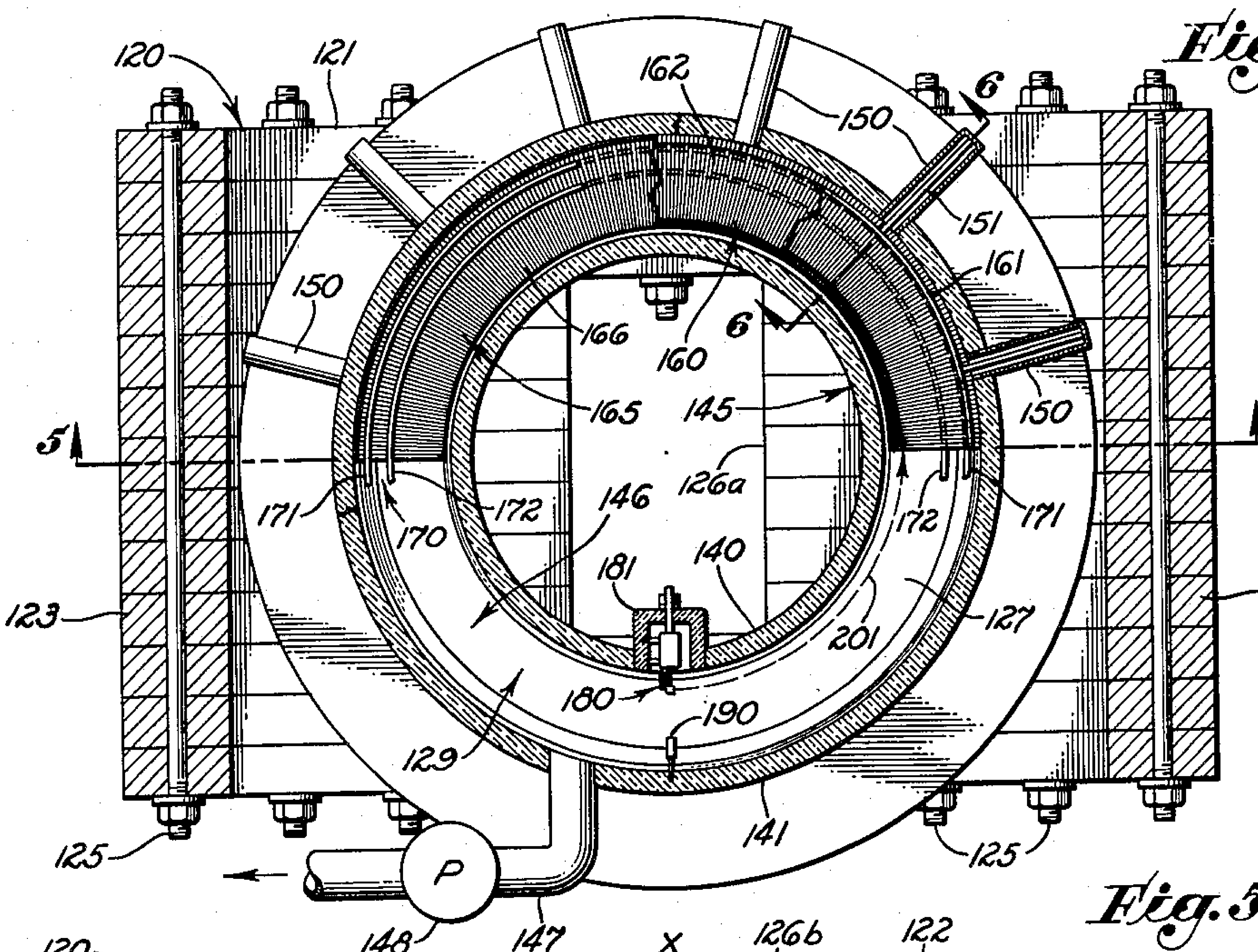

Fig. 5.

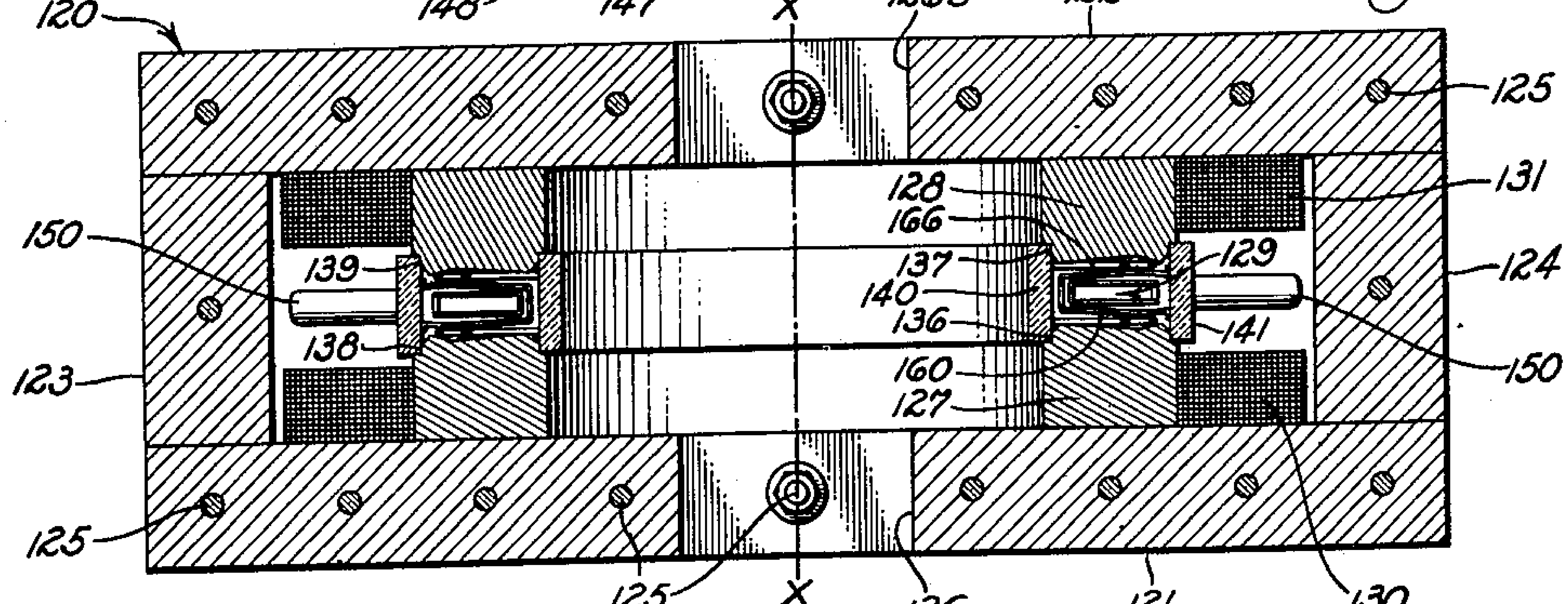

Fig. 6.

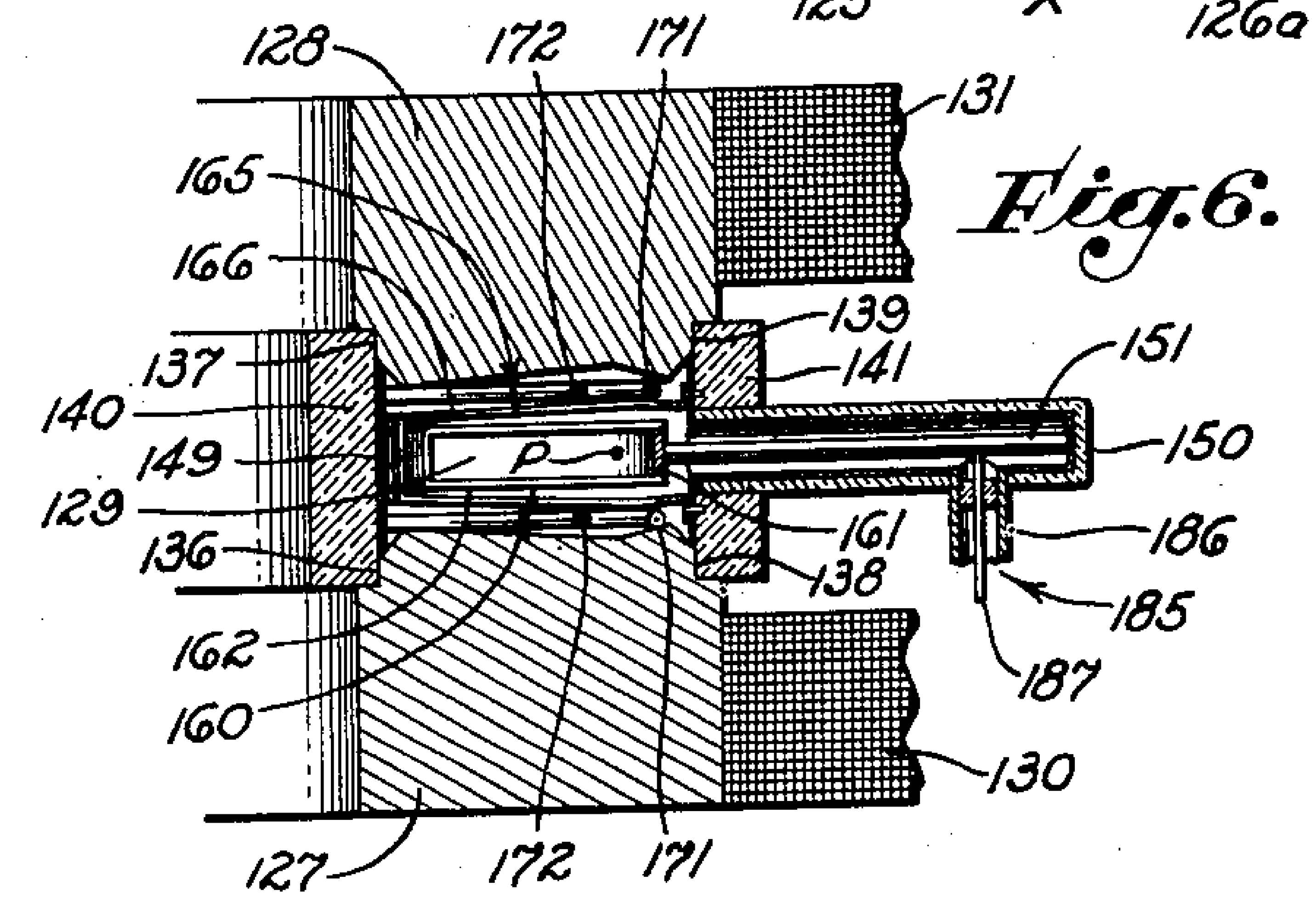

Fig. 8.

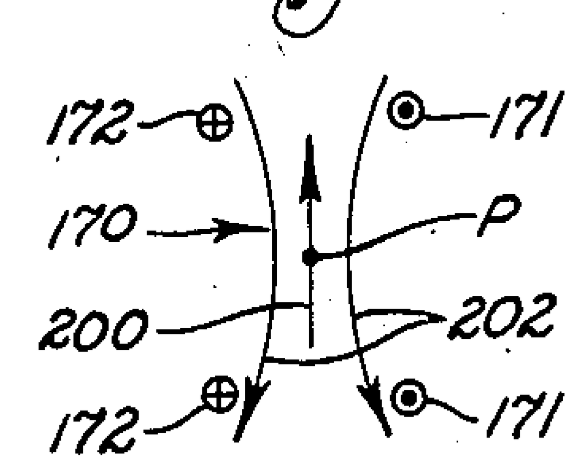

Fig. 7.

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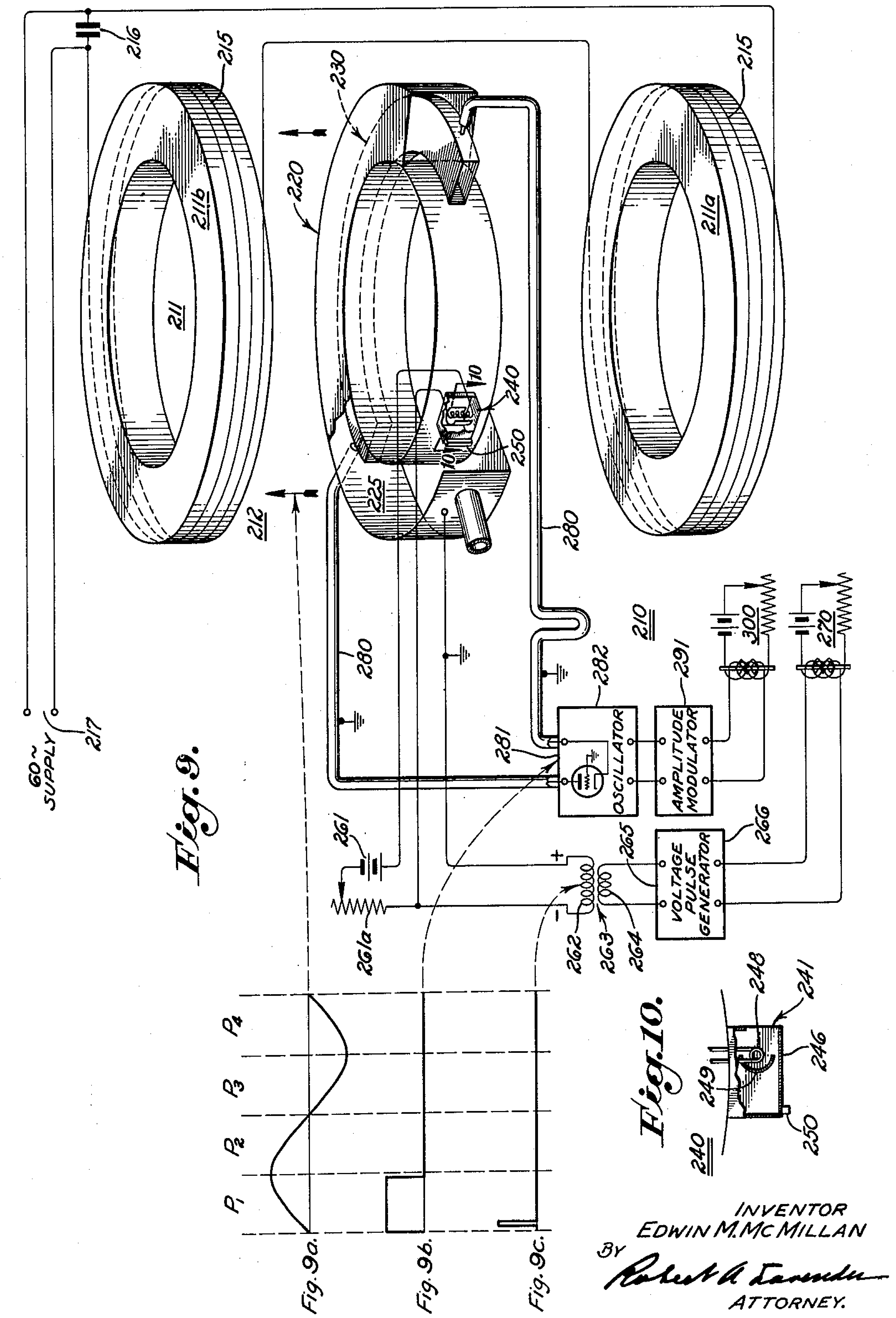

Fig. 9.

Fig. 10.

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UNITED STATES PATENT OFFICE

2,624,841

METHOD OF AND APPARATUS FOR ACCELERATING TO HIGH ENERGY ELECTRICALLY CHARGED PARTICLES

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Application May 3, 1946, Serial No. 666,908

12 Claims. (Cl. 250—27)

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This invention relates to methods and apparatus for accelerating electrically charged particles such as ions or electrons to high energy and more particularly to improvements in the art of electromagnetic acceleration of charged particles.

In the past, two types of electromagnetic accelerators have been available for accelerating charged particles to high energies, namely, cyclotrons and betatrons. In a cyclotron, charged particles are repeatedly subjected to acceleration along a spiral path between two dees disposed in a magnetic field, the acceleration being produced by a series of regularly recurring electrical impulses imparted to the charged particles across accelerating gaps between the dees. In a cyclotron, the magnetic field is maintained substantially constant and the field between the two dees is created by an oscillator operating at constant frequency. The success of the cyclotron principle depends upon the fact that the angular velocity of the particles along their paths is substantially constant regardless of their energy so that the particles travelling along curved paths in the magnetic field always enter the accelerating gaps at the same phase of oscillation. Under these circumstances, impulses imparted to the charged particles in the proper phase accumulate to increase the energy of the particles to a high value. However, it has been found that as the energy of the particles increases, the mass of the particles likewise increases, thereby causing their angular velocity to decrease and causing the particles to arrive at the region of acceleration with a gradually increasing phase lag. As a result, when the particles attain very high energies, further impulses imparted to them may decrease the energy possessed by the particles. For this reason, the maximum energy which may be imparted to charged particles in a cyclotron is seriously limited by the fact that the mass of the particles increases with their energy. This is especially true when attempts are made to utilize a cyclotron to accelerate electrons, which are of very low mass. In a cyclotron, singly charged ions have been accelerated to energies of about 40 m. e. v. But very little attempt has been made to accelerate electrons in a cyclotron.

In a betatron, charged particles, such as electrons, are directed along a circular path about the axis of a varying magnetic field having circular symmetry and the electric field induced along the path of the particles by the varying magnetic field is utilized to accelerate the particles to high energy. Because the electric field

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extends along the path of the particles and is changing in one direction only for a considerable period of time, no phase difficulties occur as in the cyclotron and the charged particles are accelerated to higher and higher energy. Eventually, however, further increase in the energy of the particles is limited by the fact that the particles lose energy by radiation. In a betatron, electrons have been accelerated to energies of about 100 m. e. v. However, the demands of modern research and industry require an instrument and a technique which will supply charged particles at very much higher energy.

Accordingly, one object of this invention is to provide a method and apparatus which will enable the acceleration of charged particles to higher energies than has heretofore been attained by the combined action of magnetic and electric fields.

Another object of the invention is to provide a method and apparatus for accelerating charged particles to energies corresponding to substantial changes in the mass of the particles.

Another object of the invention is to provide a method and apparatus for utilizing the energy thus produced.

A further object of the invention is to provide a method and apparatus employing an oscillating electric field and a magnetic field for controlling the energy of charged particles by varying the ratio of the magnetic field strength to the frequency of oscillation.

A still further object of the invention is to provide a method and apparatus employing an oscillating electric field and a magnetic field for increasing the energy of charged particles by increasing the strength of the magnetic field.

A still further object of the invention is to provide an improved method and apparatus for directing particles to a target from a region in which the particles have been accelerated to high energy by employing an oscillating electric field and a magnetic field.

A still further object of the invention is to provide a method and apparatus employing an oscillating electric field and a varying magnetic field for accelerating charged particles along closed paths in an annular region and for directing the particles to a target in the outer portion of that region.

A still further object of the invention is to provide a method and apparatus employing an oscillating electric field and a varying magnetic field for accelerating charged particles along closed paths in an annular region and for directing the particles to a target in the inner portion of that region.

A still further object of the invention is to provide an electromagnetic accelerator utilizing an electromagnet which concentrates flux in an annular region.

A still further object of the invention is to provide an electromagnetic accelerator employing a varying magnetic field and an electric field with an electrode structure which provides for minimum interaction between that structure and the magnetic field.

The present invention is based upon the discovery of the phase stability of particles travelling under certain conditions in circular orbits of a cyclotron. As an introduction to this principle, consider, for example, a conventional cyclotron having two dees disposed in a plane between and parallel to the pole faces of a magnet and defining two radially extending accelerating gaps. Charged particles which are travelling in the dees at high energy in circular paths arrive at the gaps in the same phase periodically, only if their energy is such that the angular velocity of the particles is of the value which is proper for matching the frequency of the electric field applied across the accelerating gaps, that is, only if the period of rotation of the particles in their orbits equals the period of the electric field applied across the accelerating gaps. The orbits of particles travelling in the dees are stable if, when the particles cross the accelerating gaps at the time the electric field is zero, the field is changing in such a sense that an earlier arrival of the particle results in acceleration and a later arrival of the particle results in deceleration. Under such conditions, if, for any reason, the particle arrives at a gap retarded or lagging in phase, it is decelerated to a lower energy. The resultant reduction in energy is accompanied by a reduction in mass of the particle and consequently an increase in angular velocity. This increase in angular velocity causes the particle to arrive at the next accelerating gap at an earlier phase, thus partially overcoming the phase lag. Likewise, if the particle arrives at a gap advanced or leading in phase, it is accelerated. The resultant increase in energy is accompanied by an increase in mass of the particle and consequently a decrease in angular velocity. This decrease in angular velocity causes the particle to arrive at the next accelerating gap at a later phase, thus partially overcoming the phase lead. From this it can be shown that if the equilibrium value of the energy suitable for matching the frequency of the electric field is sufficiently high, the instantaneous value of the energy of the particle oscillates back and forth on opposite sides of the equilibrium value. In this manner, according to the present invention, the energy of a group of particles travelling in substantially circular orbits in a device of the cyclotron type is phase stabilized about the equilibrium value. For convenience, energy of the equilibrium value is referred to hereinafter as the equilibrium or resonance energy. The value of the equilibrium or resonance energy depends upon the strength of the magnetic field and the frequency of oscillation of the electric field.

To utilize the principle of phase stability for accelerating charged particles to high energy according to the present invention, charged particles are injected at an appropriate phase into an annular region in which a magnetic field is crossed with an oscillating electric field so as to cause the particles to traverse curved orbits concentric with that region at an energy approximating the equilibrium energy and the ratio of the magnetic field strength to the frequency of oscillation is gradually increased. When the ratio of the magnetic field strength to oscillating frequency is thus increased, on the average a group of charged particles arrive at the accelerating gap early in phase and are thus subjected to further acceleration. As a result the equilibrium energy and hence the average energy of the group of particles is gradually increased. In the preferred form of the invention, the charged particles travelling in curved paths in a magnetic field are repeatedly subjected to lineal, i. e. tangential, acceleration by application of an electric field at constant frequency and the strength of the magnetic field is gradually increased in the region of the particle orbits. When the particles have attained the energy desired, they are deflected to a target where their energy is utilized. If the target is located outside the orbits, the magnetic field strength is suddenly reduced in order to expand the orbits quickly so that the particles strike the target. If, however, the target is located within the orbits, the magnetic field strength is increased, to contract the orbits and cause the particles to impinge upon the inner target.

An electromagnetic accelerator embodying the present invention and employing phase stability in its operation is known as a synchrotron.

The foregoing and other objects and advantages of the invention will be more readily understood by reference to the following detailed description taken in connection with the accompanying drawings wherein:

Figure 1 is a schematic wiring diagram of a synchrotron apparatus, the synchrotron itself being shown in partially exploded view;

Figs. 1*a*, 1*b*, 1*c*, 1*d* and 1*e* are graphs used in explaining the operation of various portions of the synchrotron illustrated in Fig. 1, the graphs being linked by dotted lines to the portion of Fig. 1 to which they apply;

Fig. 2 is a plan view, partly in section, of an electron injector utilized in the synchrotron of Fig. 1, taken on the line **2—2** of Fig. 1;

Fig. 3 is a vector diagram used in explaning the equations of motion of particles travelling in the orbital paths of a synchrotron;

Fig. 4 is a plan view, partly in section and partly fragmentary, showing mechanical details of a synchrotron;

Fig. 5 is an elevational view of a synchrotron of Fig. 4, taken in section on the line **5—5**;

Fig. 6 is a fragmentary view showing details of a synchrotron of Fig. 4, taken on the line **6—6**;

Fig. 7 is a graph illustrating the distribution of magnetic flux in the gap of the synchrotron illustrated in Fig. 6;

Fig. 8 is a diagram utilized in explaining the deflection of particles to the target of the synchrotron of Figs. 4, 5 and 6;

Fig. 9 is a schematic diagram of another synchrotron;

Figs. 9*a*, 9*b* and 9*c* are graphs used in explaining the operation of various portions of the synchrotron illustrated in Fig. 9, the graphs being linked by dotted lines to the portion of Fig. 9 to which they apply; and

Fig. 10 is a sectional view of an electron injector utilized in the synchrotron of Fig. 10, taken on the line **10—10**.

Referring now more particularly to Figs. 1 and 2, there is illustrated an electromagnetic accelerator embodying the present invention and known as a synchrotron. The synchrotron 10 comprises a magnetic field structure 11 and a tank 20 which are symmetrically arranged about a vertical axis $x—x$. The magnetic field structure 11 includes lower and upper coaxial pole pieces 11*a* and 11*b* which define a coaxial flux gap 12 therebetween. The pole pieces 11*a* and 11*b* are preferably in the form of annular cylinders, thereby defining a flux gap 12 of annular shape in which magnetic flux is concentrated. Likewise, the tank 20, shown partially cut away in Fig. 1, is preferably of annular shape and is so proportioned as to have its main portion disposed within the flux gap 12. Preferably, the faces of the pole pieces 11*a* and 11*b* which define the gap 12 are so shaped as to produce in the gap 12 a magnetic field which decreases slightly with increasing radial distance from the axis $x—x$. This result may be accomplished, for example, by tapering the tips of the pole pieces 11*a* and 11*b*, as is well known. The pole pieces 11*a* and 11*b* carry two series-connected sections of a magnetizing winding 15—15. This winding is shunted by a tuning condenser 16 and is connected to a source 17 of alternating current such as a 60-cycle supply. The alternating current passing through the magnetizing winding 15 produces a varying magnetic field in the gap 12, the positive direction of this field being represented by the arrows 18—18. This magnetic field varies in intensity substantially in synchronism with the current through the winding and substantially in phase therewith. The magnetic flux is thus concentrated in the region which includes the annular tank 20.

The annular tank 20 comprises concentric inner and outer cylindrical walls 21 and 22 and lower and upper annular walls 23 and 24, respectively, these walls thus forming an annular chamber 25 in the annular gap 12 in which the magnetic flux is concentrated. The walls 21, 22, 23 and 24 of the tank are preferably composed of electrically conductive material so as to shield the annular chamber or region 25 from external electric fields and the tank walls are preferably grounded. A semicircular hollow electrode 30, hereinafter called a cee electrode, is disposed within the chamber 25 concentrically therewith. This cee electrode 30 comprises concentric inner and outer semicylindrical walls 31 and 32, respectively, which are connected by lower and upper semicircular walls 33 and 34, respectively, defining a semicircular region 35 substantially free of electric field and terminating in openings 36 and 37 located at diametrically opposed positions within the chamber 25. The cee electrode 30 is suitably supported from the walls of the tank 20 and electrically insulated therefrom to facilitate applying a radio frequency voltage therebetween. A vacuum connection 26 is made to the outer wall 22 of the tank 20 in order to maintain the chamber 25 at a very high vacuum. The vacuum connection 26 is connected to suitable pumping apparatus (not shown) adapted to maintain the pressure within the chamber 25 at a suitably low value of the order of 10^{-5} mm. Hg. Preferably, the tank 20 is operated at a pressure low enough for the mean free path of high energy charged particles travelling therein to be greater than the distance to be travelled by the particles while being accelerated to the energy desired or at least of the same order as the distance to be travelled.

An electron injector 40 which is to serve as a source of electrons to be accelerated is supported within the chamber 25 on the inner wall 21 of the tank 20 at a position opposite the cee electrode 30 and substantially midway between the two openings 36 and 37 therein. A target 50 which is to be bombarded by accelerated electrons is suitably supported within the chamber 25 on the outer wall of the vessel. The electron injector 40 and the target 50 are located within the annular cylindrical region which would be defined by the cee electrode 30 if its walls were circularly extended. More specifically, the radial distance of the electron injector 40 from the axis $x—x$ of the synchrotron 10 is somewhat greater than the radial distance of the inner wall 31 of the cee electrode 30 from that axis and the radial distance of the target 50 from that axis $x—x$ is somewhat less than the radial distance of the outer wall 32 of the cee electrode 30 from that axis $x—x$.

More particularly, as shown in Fig. 2, the electron injector comprises a box-shaped anode 41 having two side walls 42 and 43, respectively, and lower and upper walls 44 and 45 supported from and electrically connected to the inner wall 21 of the tank 20 and also comprises an end wall 46 attached to the side walls 42 and 43 and to the lower and upper walls 44 and 45. The anode 41 includes an elongated rectangular opening 47 formed in the side wall 43 adjacent the end wall 46, the length of this opening 47 being parallel to the axis $x—x$ of the synchrotron 10 and located on the counterclockwise face of the anode 41. A coiled thermionically emissive cathode 48 is insulatingly supported within the anode 41, the axis of this cathode likewise being parallel to the axis $x—x$ at a radial position opposite the opening 47 in the anode 41. A semicylindrical focusing electrode 49 is arranged within the anode 41 concentrically with the filamentary cathode 48 and on the opposite side thereof from the rectangular opening 47. This electron injector 40 is thus arranged to direct electrons tangentially from the thermionically emissive cathode 48 through the opening 47 in the anode 41 in a counterclockwise direction in the magnetic field about the axis $x—x$ of the synchrotron.

The synchrotron 10 utilizes an ejector winding 60—60 comprising coil sections disposed in the gap 12 on opposite sides of the tank 20. The ejector coil 60—60 serves to expand the orbits of accelerated electrons to enable them to strike the target 50, as more fully explained hereinbelow.

Considering now the electrical circuits of the synchrotron 10, the filamentary cathode 48 is heated by means of a battery 61 which is connected to opposite ends thereof through a rheostat 61*a*. The semicylindrical focusing electrode 49 is electrically connected to either end of the filamentary cathode 48. The filamentary cathode 48 and the anode 41 are connected to opposite terminals of the secondary winding 62 of a transformer 63, the primary winding 64 of which is connected in the output terminals 65 of a voltage pulse generator 66 which is synchronized with the magnetic field set up by the coils 15 by means of a timing device 70. The timing device 70 comprises a peaking transformer 71 which includes a Permalloy strip 72 mounted within the magnetic field produced by the magnetizing winding 15. This peaking transformer comprises primary and secondary windings 73 and 74, respectively. The primary winding 73 is connected to opposite terminals of a biasing battery 75 through a rheostat 76 and the secondary winding 74 is suitably connected to terminals 73 of the voltage pulse generator 66. With this timing device 70, an impulse is transmitted from the peaking transformer 71 to the voltage pulse generator 66 each time the field through the Permalloy strip 72 passes through zero, the total flux through this strip 72 being determined partly by the alternating magnetomotive force created therein by the leakage flux produced by the magnetizing winding 15 and partly by the magnetomotive force created therein by the current flowing from the battery 75. This timing device 70 serves to cause electrons to be injected into the chamber 25 once in each cycle of operation and to synchronize the injection of electrons with the generation of the magnetic field passing through the gap 12, as more fully explained hereinbelow. The desired synchronization is achieved by adjustment of the current passing through the primary winding 73. The duration of this voltage pulse is preferably long compared to the period of the radio frequency voltage impressed upon the cee electrode 30.

The cee electrode 30 is suitably connected at two spaced points through two coaxial cables 80—80 to the output 81 of a radio frequency oscillator 82 which includes an output tube 83 having its grid 84 grounded to the tank 20 and its anode 85 and the cathode 86 connected across the output terminals 81. More particularly, the outer conductors 88—88 of the coaxial cables 80—80 terminate at the outer wall 22 of the tank 20 and are grounded and the inner conductors 89—89 connect directly with the cee electrode 30. Preferably the connections to the cee electrode 30 and the walls of the tank 20 are made through suitable impedance matching devices (not shown). In order that the potential at the two points of the cee electrode 30, to which the inner conductors 89—89 are connected, shall be in phase, one of the conductors 89—89 includes an extended element 90 for effectively adjusting the relative electrical lengths of the conductors.

The oscillator 82 is operated at constant frequency and the amplitude of its output is suitably modulated by means of an amplitude modulator 91 which is in turn controlled by a timing device 100. This timing device 100 is of the same type as that hereinabove described and comprises a second peaking transformer 101 which includes a Permalloy strip 102 mounted within the magnetic field produced by the magnetizing winding 15. This peaking transformer 101 also comprises primary and secondary windings 103 and 104, respectively. The primary winding 103 is connected to opposite terminals of a second biasing battery 105 through a second rheostat 106 and the secondary winding 104 is suitably connected to a control point 108 of the amplitude modulator 91. With this timing device 100, an impulse is transmitted from the second peaking transformer 101 to the amplitude modulator 91 at the moment that the field through the Permalloy strip 102 thereof passes through zero, the total flux through this strip being determined partly by the alternating magneto-motive force created therein by leakage flux produced by the magnetizing winding 15 and partly by the flux created therein by the current flowing from the battery 105. This timing device 100 serves to cause the oscillator to be effectively turned on for a definite time interval once during each cycle of operation and to synchronize the modulation of the oscillator 82 with the generation of the magnetic field passing

through the gap 12, as more fully explained hereinbelow. The desired synchronization is achieved by adjustment of the current passing through the primary winding 103.

The ejector winding 60—60 is connected to the output of a current pulse generator 110 which is suitably connected to the source 17 of A. C. power through a phase shifter 111. This phase shifter 111 is designed to synchronize the production of current pulses in the output of the current pulse generator 110 with the varying magnetic field, as more fully explained hereinbelow. The duration of the current pulse produced at the output of the current pulse generator 110 is preferably long compared to the period of radio frequency output of the oscillator 82.

Considering now the synchronous operation of the magnetizing winding 15, the electron injector 40, the oscillator 82, and the ejector winding 60—60 during a single cycle of operation. For convenience, the cycle of operation is divided into four quarters Q_1, Q_2, Q_3 and Q_4, as illustrated in the coordinated graphs represented in Figs. 1*a*, 1*b*, 1*c*, 1*d* and 1*e*. Referring to Fig. 1*a*, it is to be noted that the current through the magnetizing winding 15 varies sinusoidally; the intensity of the current starting at zero and then increasing in one direction in the first quarter Q_1 of the cycle of operation, then decreasing but remaining in the same direction in the second quarter Q_2 of the cycle of operation and then increasing in the third quarter Q_3 of the cycle of operation in the opposite direction and then decreasing while still flowing in the latter direction in the fourth quarter Q_4 of the cycle of operation. Referring now to Fig. 1*d*, there is shown a substantially square wave and this may be referred to as the "envelope" for the radio frequency oscillations produced by the oscillator 82. In other words, the output of the oscillator 82 is modulated or keyed to form pulses as shown in Fig. 1*d* and each of these pulses consists of a train of radio frequency oscillations. It is to be noted that the amplitude of the output of the radio frequency oscillator 82 is of a relatively high value during the first quarter Q_1 of the cycle of operation and is zero during the other three quarters Q_2, Q_3 and Q_4, this result being achieved partly by suitable design of the oscillator 82 and the amplitude modulator and partly by suitable adjustment of the timing device 100. Referring to Fig. 1*e*, it is to be noted that the voltage pulse generated at the secondary 62 of the transformer 63 attains a high value shortly after the commencement of the first quarter Q_1 of the cycle of operation and is zero at all other times, this result being achieved partly by the design of voltage pulse generator 66 and partly by adjustment of the timing device 70. Referring to Fig. 1*b*, it is to be noted that the current generated by the current pulse generator 110 and applied to the ejector winding 60—60 attains a high value at the commencement of the second quarter Q2 of the cycle of operation and is substantially zero at all other times, this result being achieved by suitable design of the current pulse generator 110 and the phase shifter 111. By suitably arranging the magnetizing winding 15—15 and the ejector winding 60—60, the magnetic fluxes produced simultaneously thereby are in opposite directions so that at the moment current is applied to the ejector coil 60—60 by the current pulse generator 110, the intensity of the magnetic field strength passing through the tank 20 is rapidly reduced momentarily. Thus, referring to Fig. 1*c*, the combined effects of the magnetizing winding 15—15 and the ejector winding 60—60 in producing magnetic flux through the tank is illustrated. Here it is to be noted that in the first quarter Q_1 of the cycle of operation, the intensity of the magnetic field is directed upward and gradually increases sinusoidally and is suddenly depressed momentarily at the commencement of the second quarter Q_2 of the cycle of operation and thereafter continues to change sinusoidally, the magnetic field being directed upward during the first and second quarters Q_1 and Q_2 of the cycle of operation and downward during the third and fourth quarters Q_3 and Q_4.

Considering now the action of the synchrotron 10 in accelerating electrons to high energy and causing them to impinge upon the external target 50, it is to be noted that during the first quarter Q_1 of the cycle of operation, the voltage between the cee electrode 30 and the tank 20 changes at radio frequency and that during this quarter Q_1, the intensity of the magnetic field passing through the tank 20 gradually increases from zero to a relatively high value at a relatively low rate. While the intensity of the magnetic field is still very low, a negative voltage pulse created in the secondary 62 of the transformer 63 is impressed upon the filamentary cathode 48 and focusing electrode 49 for a short interval of time, causing electrons to be projected from the filamentary cathode 48 through the opening 47 in the anode 41 along a curved path. The path initially followed is in a counterclockwise direction about the axis x—x of the synchrotron 10 determined primarily by three factors, namely (1) the intensity of the magnetic field, (2) the radial gradient of the magnetic field intensity, and (3) the energy with which the electrons are injected. Some of the electrons arrive at the opening 36 in the cee electrode 30 in phase with the radio frequency voltage impressed thereon and some out of phase. Those electrons which arrive at the opening 36 at the time that the voltage on the cee electrode 30 is passing through zero enter the space 35 within the cee electrode 30 without acceleration or deceleration. Those electrons which arrive at the opening 36 in the cee electrode 30 somewhat out of phase with the voltage on the cee electrode are either accelerated or decelerated, as the case may be, as more fully explained in connection with the discussion of phase stability hereinabove. Electrons which arrive at the opening 36 in the cee electrode within a predetermined range of phase and energy constitute a group of electrons which are phase-stabilized. Electrons which arrive at the opening 36 of the cee electrode outside of this range are not phase-stabilized but eventually lose their energy and are scattered to the walls of the tank 20. In order to generate a group of phase-stabilized electrons, electrons are projected from the injector 40 with an energy equal to the equilibrium energy corresponding to the strength of the magnetic field at the time of injection and the radial distance of the point of injection from the axis x—x, as more fully explained hereinbelow. By suitably choosing the voltage characteristics of the oscillator 82 and the voltage pulse generator 66 in relationship to the dimensions of the tank 20 and its component parts and the gradient of the magnetic field intensity and the rate of change of the magnetic field intensity at the time of injection, many of the electrons which enter the cee electrode 30 pass the injector 40 in the space between the injector 40 and the target 50 in their first orbital revolution within the chamber 25. The electrons are injected into the chamber 25 with an energy greater than that corresponding to the radial position of the injector. In such a case the electrons injected seek an equilibrium orbit of greater radius and oscillate back and forth across this orbit. Thus, a substantial portion of these electrons miss the injector as they revolve above the axis x—x of the synthrotron and become phase stabilized. As this group of electrons alternately enter and emerge from the cee electrode 30 as the magnetic field strength is increased, the equilibrium energy of this group of electrons also increases. As the energy of the electrons increases, the mean radius of their orbits likewise increase so that the group of electrons spiral outward from a position adjacent the inner wall 31 of the cee electrode 30 to an outer position adjacent the outer wall 32 thereof.

Finally, at the end of the first quarter Q_1 of the cycle of operation, the radio frequency oscillator 82 is shut off and the intensity of the magnetic field is suddenly reduced, thereby expanding the orbits in which the electrons travel. As these orbits expand, the highly accelerated electrons impinge upon a target 50 where their energy is utilized such as for the production of X-rays or nuclear reactions, as the case may be. In the remaining portion of the cycle of operation, no electrons are accelerated. Thereafter, the process of injection, acceleration, and orbital expansion is periodically resumed when the intensity of the magnetic field again begins to increase in an upward direction.

As previously mentioned, the successful operation of the synchrotron depends upon the phase stabilization of the orbits in which the electrons travel. Considering this principle in greater detail, it can be shown that the equilibrium energy of the electrons at any time during the acceleration is given by the equation:

$$E_0=(300cH)/(2\pi f) \qquad (1)$$

where

E_0=equilibrium energy including both kinetic energy and rest energy

c=velocity of light

H=intensity of magnetic field through which the electron is travelling

f=frequency of oscillator

It can also be shown that the energy of an electron is given by the equation:

$$E=E_0[1-(d\phi)/(d\theta)] \qquad (2)$$

where

θ=angular position of the electron in its orbit,

ϕ=phase lag of the voltage impressed upon the cee electrode 30 at the moment the electron reaches an opening therein, or the phase lead of the angular position of the electron at the time that the voltage impressed upon the cee electrode 30 is zero,

E=the total energy of the electron including both the kinetic energy and the rest energy.

More specifically, the total energy of the particle is given by the equation:

$$E=\frac{Er}{\sqrt{1-\beta^2}} \qquad (3)$$

where the rest energy

$$Er=m_0C^2$$

and m_0=the rest mass of the electrons, and

$$\beta=\frac{v}{c}$$

where v=speed of the electrons.

It can also be shown that the relative phase ϕ between the electron position and the radio frequency voltage is given by the following equation:

$$2\pi\frac{d}{d\theta}\left(E_0\frac{d\phi}{d\theta}\right)+V\sin\phi=\left[\frac{1}{f}\frac{dE_0}{dt}-\frac{300}{c}\frac{dF_0}{dt}+L\right]+\left[\frac{E_0}{f^2}\frac{df}{dt}\right]\frac{d\phi}{d\theta'} \quad (4)$$

where

V=the energy gained from the electric field during each orbital revolution of an electron when the electron enters the semicircular electrode at the most favorable phase, that is, the peak voltage of the oscillator **82** output when the output is sinusoidal,

F_0=the total magnetic flux enclosed by the orbit of an electron possessing energy of the equilibrium value E_0,

L=energy lost per orbital revolution as a result of radiation from the electrons and their collision with molecules of gas in the chamber **25**, and

t=time.

It is to be noted that Equation 4 takes into account possible changes in the intensity of the magnetic field and possible changes in the frequency of the radio frequency oscillator **82**. Where, as in the present instance, the frequency is constant, Equation 4 reduces to the following:

$$2\pi\frac{d}{d\theta}\left(E_0\frac{d\phi}{d\theta}\right)+V\sin\phi=\left[\frac{1}{f}\frac{dE_0}{dt}-\frac{300}{c}\frac{dF_0}{dt}+L\right] \quad (5)$$

It can also be shown that the radius of the orbit in which an electron is travelling is given by the following equation:

$$R=(E^2-Er^2)^{1/2}/300H \quad (6)$$

The values of the energy given in Equations 1, 2, 3, 4, 5, and 6 are in electron volts, the magnetic quantities in these equations are in electromagnetic units, angles are in radians and the other quantities are in C. G. S. units. From an analysis of the foregoing equations, it can be shown that if the equilibrium value E_0 of the energy increases with time at a sufficiently rapid rate, the instantaueous values of the energy E oscillate back and forth about the equilibrium value E_0 and that the amplitude of the difference between the instantaneous value E of the energy and the equilibrium value E_0 gradually decreases. It can also be shown that under the same conditions, the instantaneous value of the phase difference ϕ oscillates about a zero value.

Considering Equations 1 and 6 together, it can be shown that as the energy of the electrons increases, the orbits asymptotically approach a radius

$$R_m=\frac{c}{f}$$

which, it is to be noted, means that the distance travelled in a single orbital revolution of the electrons approaches the wave length of the radio frequency waves generated by the oscillator **82**. In this connection, it is also to be noted that as the energy of the particles increases, the speed of the particles gradually approaches the speed of light, and further increases in energy have very slight effect upon the speed.

More particularly, if the electrons are injected into the chamber with an energy of about 300 kv. at an initial orbital radius of 78 cm. and are subjected to a radio frequency field of 48 megacycles per sec. and the magnetic field strength changes at 60 cycles per sec. to a value of 10,000 gauss, the electrons are accelerated to an energy of 300 m. e. v. in the first quarter Q_1 of the cycle of operation and the final orbital radius of the particles is 100 cm. In this operation, if the voltage V equals 1000 volts, the maximum phase shift ϕ is 13° and the electrons revolve about the axis of the magnetic field about 20,000 times, revolving about 22 times during a single oscillation of the energy and phase at the commencement of acceleration and about 440 times for a single oscillation of the energy and phase during the final portion of the acceleration. Also, during this operation, the instantaneous value of the energy E of the accelerated electrons differs from the equilibrium value E_0 at the most by about 6.3% at the time of injection and then diminishes as the equilibrium energy E_0 increases.

In considering the acceleration of charged particles by the process hereinabove described, it is to be noted that forces of two different origins act upon the electrons in order to accelerate them to higher and higher energies. One of these forces is supplied by the electric fields created at the openings **36** and **37** of the cee electrode **30**. The other force is supplied by the electric field induced along the orbits of the electrons by the changing magnetic field. The first of these forces is of the same type which is utilized in a cyclotron. The second of these forces is of the type which is utilized in a betatron.

Considering now the detailed structure of an electromagnet and a tank suitable for use in the synchrotron hereinabove described, reference is now made to Figs. 4, 5 and 6. Such an electromagnet **120** comprises lower and upper yokes **121** and **122** interconnected at their ends by upright legs **123** and **124**. The yokes **121** and **122** and the legs **123** and **124** are of laminated construction, being constructed from a series of soft iron plates rigidly held together by suitable means such as bolts **125**. The two yokes **121** and **122** are provided with two vertically aligned rectangular openings **126a** and **126b**, respectively, at the centers thereof in order to provide access for workmen to other parts of the apparatus. Between the two yokes **121** and **122** and surrounding the two rectangular openings **126a** and **126b** are located vertically aligned lower and upper annular pole pieces **127** and **128** defining an annular gap **129**. Lower and upper sections **130** and **131** of a magnetizing coil encircle the lower and upper pole pieces **127** and **128**, respectively, these coils being located in the magnetic structure adjacent the yokes **121** and **122**, respectively, in the space between the pole pieces **127** and **128** and the legs **123** and **124**.

The tips of the two pole pieces **127** and **128** are preferably so shaped that the flux density of the magnetic field created in the gap **129** between the pole pieces **127** and **128** varies slightly as an inverse function of the distance from the axis $x—x$ of the magnetic structure **120** and are furthermore so shaped that the gradual diminution of flux densiity in a radial direction extends over as wide a region as possible. Such a distribution of magnetic flux facilitates focusing an electron beam in the center of the gap, and the specific gradient of magnetic field intensity is selected to facilitate injected electrons clearing the injector and the walls of the cee electrode, as explained hereinabove. In the design illustrated, the desired distribution of magnetic flux is achieved by tapering the faces of the pole pieces 127 and 128 so as to provide a gradual enlargement of the gap 129 with increasing radius and shimming the peripheral edges of the pole tips so as to provide a reduction in thickness of the gap 129 at the inner and outer edges thereof. In practice, a magnetic flux density that varies inversely as about the five-eighths power of the radial distance, is found suitable, thus establishing a flux density gradient which varies gradually throughout the width of the gap 129. as illustrated in Fig. 7.

The inner walls of the pole tips are tapered outwardly toward the gap and are provided with annular grooves 136 and 137 on the outwardly tapering surfaces, these grooves being adapted to rigidly engage an inner ring 140. The outer walls of the pole tips are tapered inwardly toward the gap and are provided with annular grooves 138 and 139 on the inwardly tapering surfaces, these grooves being adapted to engage an outer ring 141. The contacts between the inner and outer rings 140 and 141 and the pole pieces 127 and 128 are hermetically sealed to the tank 145 enclosing an annular chamber 146 between the pole pieces 127 and 128. A vacuum line 147 including a pump 148 connected to the outer wall 141 of the tank 145 is utilized for maintaining a high vacuum in the chamber 146. Preferably, the inner and outer walls 140 and 141 of the tank 145 are composed of a nonmagnetic electrically insulating nonporous material such as Textilite and the interior surfaces of these walls are metallically coated, such as with silver plate 149, which cooperates with the faces of the pole pieces 127 and 128 to form a chamber which is shielded from external electric fields. The inner and outer rings 140 and 141 constitute inner and outer walls. respectively, and the faces of the lower and upper pole pieces 127 and 128 constitute the lower and upper walls, respectively, of a tank which defines an annular chamber in the gap between the pole pieces, which serves as a region for electron acceleration.

Protruding from the outer wall 141 is a plurality of radially extending tubes 150, these tubes being located on one side of the tank 145 and being regularly spaced along the circumference thereof. The tubes 150 are closed at the outer ends and are preferably composed of nonmagnetic electrically insulating nonporous material, such as silicon bonded glass fiber. In order to complete the electrical shielding for the chamber 146, the interior walls of these tubes are also metallically coated, such as by silver plate.

A semicircular cee electrode 160 is supported within the chamber 146 by means of supporting arms or stems 151 which are arranged coaxially with the tubes 150. These support arms 151 are preferably composed of metallic or ceramic materials. If composed of the latter, they are preferably metallically coated with a surface which is in electrical communication with the other coatings on the interior surfaces of the tank walls 140 and 141 and the tube 150 and the pole pieces 127 and 128. In effect, the support arms and tubes comprise impedance matching coaxial lines for supplying electrical energy to the interior of the tank 145. as more fully explained hereinbelow. More particularly, the cee electrode 160 comprises an upright semicircular rigid metallic member 161 arranged near the outer edge of the gap 129 between the pole pieces 127 and 128 and also comprises a plurality of metallic hairpin-shaped members 162 arranged in vertical planes and extending radially inward toward the axis $x—x$ of the tank. The semicircular member 161 and the hairpin members 162 together define a semicircular or cee electrode 160 which encloses a semicircular region which is shielded from external electric fields, thus defining a substantially electrically field-free semicircular region in one-half of the tank. The semicircular region in the remaining half of the tank is also substantially free of electric fields. By applying a radio frequency voltage between cee electrode 160 and the walls of the tank 145, an oscillating electric field is created at the diametrically opposed openings of the cee electrode 160, thus in effect establishing two accelerating gaps at these positions. In order to control the shape of the electric fields at the openings of the cee electrode 160 when a potential difference is applied between the cee electrode 160 and the walls of the tank 145, the cee electrode 160 is enclosed by an auxiliary concentric shield 165 arranged within the gap 129. This shield 165 comprises a plurality of radially extending metallic hairpin members 166 arranged in vertical planes and suitably secured to the outer wall 141 of the tank 145 in electrically conducting relation to the metallic coating 149 on the interior surface thereof. By utilizing a cee electrode 160 and a shield 165 of thin wire structure, as described, eddy current losses therein are reduced to a minimum and a minimum phase lag exists between the changing magnetic field which penetrates the region of the tank 145 including the cee electrode 160 and the shield 165 and the changing magnetic field in the remaining portion of the tank 145. It is to be understood, of course, that if further reduction in this phase difference is desired, another cee electrode and shield may be arranged in the other half of the tank 145 and the latter cee electrode and shield grounded without otherwise affecting the operation of the synchrotron.

An ejector winding 170 is arranged within the gap and concentric with the magnetic structure 120. This ejector winding comprises lower and upper outer turns 171—171 and lower and upper inner turns 172—172. The outer turns 171—171 are arranged externally of the maximum orbit indicated by the point P in which accelerated electrons travel. The inner turns 172—172 are arranged internally of this orbit indicated by the point P. The two outer turns 171—171 are connected to carry current in one direction and the two inner turns 172—172 are connected to carry current in the opposite direction so that an annular magnetic field is created in the region of the orbit P in opposition to the magnetic field produced there by the magnetizing coil.

An electron injector 180 is mounted within the chamber 146 adjacent the inner wall 140 of the tank 145 and is supported therein by means of a tubular connection 181 which is hermetically sealed on the inner wall 140 of the tank 145 and extends radially outward thereof toward the axis $x—x$. This injector is so positioned as to project electrons peripherally within the chamber 146 at such a radial position that the electrons may enter the space within the cee electrode 160. This may be readily achieved by locating the injector 180 at a point half way between the openings in the cee electrode 160 and at a greater radial distance from the axis x—x of the tank 145 than the inner wall of the cee electrode 160.

A target 190 which is to be bombarded by accelerated electrons is suitably supported within the chamber 146 at a position opposite the injector 180, this position being so located that accelerated electrons may be projected thereto by operation of suitable means such as the ejector coil 170.

Without describing in detail the construction of the injector 180, it is sufficient to state that this injector may be of the same type as that previously described in connection with Figs. 1 and 2 and that the cathode thereof may be electrically connected to a battery 61 and to a source of high voltage, such as the voltage pulse generator 66. The cee electrode 160 is connected to the output of a radio frequency generator such as the oscillator 82 of Fig. 1 by means of coaxial cables 185 having their outer conductors 186 in electrical communication with the portion of the metallic coating 149 within the tube 150 and their inner conductors 187 in electrical communication with the stems 151. Preferably the impedances of the coaxial cables 185 when so connected match the impedance of the coaxial lines provided by the tubes 150 and stems 151.

Considering now the operation of a synchrotron utilizing the electromagnet and tank illustrated in Figs. 4, 5 and 6, when connected to electrical supplies in the manner previously described in connection with Fig. 1, it is to be noted that the output of the oscillator 82 is fed to the cee electrode 160 along two of the stems 151, and that the two points to which the opposite terminals of the oscillator 82 are connected operate at the same phase and voltage even though the voltages at the two output terminals of the oscillator 82 are out of phase. In operation, at the time that the cee electrode 160 is thus energized by the oscillator 82, a magnetic field which is directed upward is created in the gap 129 between the pole pieces 127 and 128, as indicated by the arrow 200 of Fig. 8, and the intensity of this field gradually increases in a sinusoidal manner. While the magnetic field is still of a relatively low value, electrons are projected from the injector 180 into the chamber 146 and travel therein in a counterclockwise direction along the path indicated by the arrow 201 in Fig. 4. The group of electrons which enter the cee electrode 160 in the proper phase are thereafter repeatedly subjected to acceleration by electrical fields which are created at the openings of the cee electrode 160 parallel to their trajectories. As a result of the acceleration of the electrons, their orbits gradually increase in radius until at the time the magnetic field strength has reached the maximum value, the orbits have attained their maximum radius at a position indicated by the point P in Figs. 6 and 8. When the electrons have thus attained the energy desired, the cee electrode 160 is de-energized and brought to ground potential. At the same time, the ejector coil is energized and current flows clockwise in the outer turns 171—171 and counterclockwise in the inner turns 172—172 thereof, thus creating a flux indicated by the arrows 202 in opposition to the main flux 200 through the gap 129 and suddenly reducing the strength of the magnetic field in the region traversed by the electrons after they have attained their full energy, as illustrated in Fig. 8. As a result of the reduction of the strength of the magnetic field, the orbits are expanded and the accelerated electrons impinge upon the target 190 where their energy is utilized.

Referring now to Figs. 9 and 10, there is illustrated a modified synchrotron that also embodies the features of the present invention. This synchrotron 210 is of a construction similar to that previously described except for the differences pointed out hereinbelow, the main differences residing in the location of the target, the omission of the ejector winding, and the constants of the remaining electrical circuits.

This synchrotron 210, like that previously described, comprises a magnetic field structure 211 provided with annular pole pieces 211a and 211b and an evacuated annular electrically shielded tank 220 which defines a chamber 225 disposed in the annular gap 212 between the pole pieces. The pole pieces carry two series-connected sections of the magnetizing winding 215—215 which is connected to a source 217 of alternating current and is shunted by a tuning condenser 216.

The annular tank 220 encloses a cee electrode 230 which is disposed concentrically therein. It also includes an electron injector 240 provided with a box-shaped anode 241, a filamentary cathode 248 and a focusing electrode 249. In this synchrotron 210, the target 250 which is to be bombarded by accelerated electrons is supported on the end wall 246 of the lectron injector 240, that is, within the minimum radius of the orbits in which the electrons are to be accelerated after their first revolution.

Considering now the electrical circuits of this synchrotron 210, the filamentary cathode 248 of the electron injector 240 is heated by means of a battery 251 which is connected to opposite ends thereof through a rheostat 261a and the cathode 248 and the anode 241 of the electron injector 240 are connected to opposite terminals of the secondary winding 262 of a transformer 263, the primary 264 of which is connected to the output 265 of a voltage pulse generator 266. The operation of the pulse generator 266 is synchronized with the magnetic field by means of a timing device 270, as hereinabove described. Also, the cee electrode 230 is connected through two coaxial cables 280—280 to the output 281 of the radio frequency oscillator 282, the output of which is suitably modulated by means of an amplitude modulator 291 which is in turn controlled by a timing device 300, as previously described. The amplitude modulator 291 of this synchrotron 210 differs from that previously described with respect to the length of the period during which radio frequency voltages appear at the output 281 of the oscillator 282, as more fully described hereinbelow.

Considering now the synchronous operation of the magnetizing winding 215—215, the injector 240, and the oscillator 282, for convenience the cycle of operation is divided into four quarters P_1, P_2, P_3 and P_4, as illustrated in the graphs represented in Figs. 9a, 9b and 9c. Referring to Fig. 9a, it is to be noted that the current through the magnetizing winding 215—215 varies sinusoidally, the intensity of the current starting at zero and increasing in one direction in the first quarter P_1 of the cycle of operation, reaching its maximum value at the end of the first quarter. Inasmuch as the magnetic flux created in the gap 212 between the pole pieces 211a and 211b is in phase with the current through the magnetizing winding, the intensity of the magnetic field increases substantially sinusoidally during the first quarter P_1 of the cycle of operation and thereafter changes in the usual sinusoidal manner, the magnetic field being directed upward during the first and second quarters P_1 and P_2 of the cycle of operation and downward during the third and fourth quarters P_3 and P_4. Referring now to Fig. 9b, it is to be noted that the amplitude of the output of the radio frequency oscillator **282** is of a relatively high value throughout a large portion of the first quarter P_1 of the cycle of operation and is zero during the remaining portion of the cycle of operation, the output being increased from zero to its maximum value at the commencement of the cycle of operation at about the time that the strength of the magnetic field in the gap is zero and being decreased to zero from its maximum value shortly before the intensity of the magnetic field reaches its maximum value. Referring now to Fig. 9c, it is to be noted that the voltage pulse generated at the secondary **262** of the transformer **263** attains a high value shortly after the commencement of the first quarter P_1 of the cycle of operation while the strength of the magnetic field is low and the oscillator output is high and is zero at all other times.

Considering now the operation of this synchrotron **210** in accelerating electrons to high energy and causing them to impinge upon the internal target **250**, some of the electrons which are projected from the injector **240** into the chamber **225** repeatedly enter and emerge from the cee electrode **230** and are accelerated to high energy under the combined influence of the increasing magnetic field and the alternating electric fields created at the openings in the cee electrode **230**, as more fully explained hereinabove. Also, as the energy of the electrons increases, the radii of their orbits likewise increase so that the orbits spiral outward in circles of increasing radius to an outer position adjacent the outer wall of the cee electrode **230**. Finally, when the output of the radio frequency oscillator is reduced to zero and while the intensity of the magnetic field continues to increase, the electrons lose energy by radiation and the orbits in which the particles travel contract, partly as a result of this loss of energy and partly as a result of the subsequent increase in the strength of the magnetic field. When these orbits contract sufficiently, the highly accelerated electrons impinge upon the target **250** which is disposed within their orbits where their energy is utilized. In the remaining portion of the cycle, no electrons are accelerated. Thereafter, the process of injection, acceleration, and orbital contraction is periodically resumed each time the intensity of the magnetic field again passes through zero in an upward direction.

In the description of the synchrotrons hereinabove described, it has been shown that electrons which are injected into an annular tank adjacent the inner edge thereof may be accelerated under the combined influence of an increasing magnetic field and an alternating electric field and that these accelerated electrons may be caused to impinge upon a target which is disposed within the tank either internally or externally of the orbits in which the accelerated electrons travel.

In the synchrotrons hereinabove described, the energy of the accelerated electrons is increased by increasing the strength of the magnetic field in which the electrons travel during the time that they are subjected to the influence of an oscillating electric field of constant frequency. It is to be noted, however, that the advantages of the invention may also be attained if the electrons travel in a magnetic field of constant strength and are subjected to the influence of an oscillating electric field, the frequency of which is gradually reduced during the period of acceleration. Thus, by referring to Equation 1, it is to be noted that the equilibrium energy of a group of electrons may be increased in accordance with the present invention by increasing the ratio of the magnetic field strength to the frequency of oscillation of the electric field during the period in which acceleration of the electrons is desired. In the preferred form of this invention, electrons are accelerated to high energy by increasing the strength of the magnetic field with or without reducing the frequency of oscillation. When the ratio of field strength to frequency is changed in this manner, a minimum radial difference between the initial and final orbits is attained, thus effecting an economy in the design of the magnetic field structure required to impart a predetermined energy to the electrons.

While the invention has been described with particular reference to the acceleration of electrons, it will be appreciated that it is also applicable to the acceleration of other electrically charged particles such as positive ions. In any event, with the synchrotron, charged particles may be accelerated to energies in the billion volt range and thus permit the exploration of X-ray and nuclear phenomena requiring higher energy in their study than has heretofore been available in electromagnetic accelerators.

It will therefore be understood that this invention is not to be limited to the details of the structure and methods of operation hereinabove described but that many modifications may be made in the apparatus and method within the scope of the following claims.

What is claimed is:

1. Apparatus for changing the energy of charged particles comprising means for establishing a magnetic field, means for projecting charged particles into said field along a path transversely thereof, means including a source of alternating electric potentials for revolving the particles in said magnetic field, and means for varying the ratio of the magnetic field strength to the frequency of said alternating electric potentials as said particles revolve whereby the resonant energy of the particles is changed.

2. Apparatus for accelerating charged particles to high energy comprising means for establishing a magnetic field, means for projecting charged particles into said field along a path transversely thereof, means including a source of alternating electric potentials for accelerating said particles along curved paths in said magnetic field whereby the energy of the particles is increased, and means for increasing the ratio of the magnetic field strength to the frequency of said alternating electric potentials as the particles move in said curved paths whereby the resonant energy of the particles is increased.

3. Apparatus for accelerating charged particles to high energy comprising means for establishing a magnetic field, means for projecting charged particles into said field along a path transversely thereof, means including a source of alternating electric potentials having a constant frequency for accelerating said particles along curved paths in said magnetic field whereby the energy of the particles is increased, and means for increasing the strength of the magnetic field as the particles

move in said curved paths whereby the resonant energy of the particles is increased.

4. Apparatus for accelerating charged particles to high energy comprising means for establishing a magnetic field, means including electrodes for defining two semicircular regions in said magnetic field, each of said regions being substantially free of electric fields, means including a source of alternating electric potentials connected to said electrodes for causing the relative potentials of said regions to oscillate whereby charged particles are rapidly accelerated to and from one region to the other, and means for increasing the ratio of the magnetic field strength to the frequency of said alternating electric potentials as said particles move in said region whereby the resonant energy of the accelerated particles is increased.

5. Apparatus for accelerating charged particles to high energy comprising means for establishing a magnetic field, means including electrodes for defining two semicircular regions in said magnetic field, each of said regions being substantially free of electric fields, means including a source of alternating electric potentials having a constant frequency connected to said electrodes for causing the relative potentials of said regions to oscillate whereby charged particles are rapidly accelerated to and from one region to the other, and means for increasing the strength of the magnetic field as said particles move in said regions whereby the resonant energy of the accelerated particles is increased.

6. Apparatus for altering the energy of charged particles comprising means for establishing a magnetic field, means defining a closed region for the travel of charged particles along curved paths in said magnetic field, means for altering the strength of said magnetic field, means including electrodes adjacent said paths and an oscillator having a constant frequency connected thereto for repeatedly applying electric field forces along said paths, and modulating means cooperating with said field generating means for effectively energizing said electrodes with the output from said oscillator while the strength of said magnetic field is at one value and for effectively de-energizing said electrodes when the strength of said magnetic field is at another value.

7. Apparatus for accelerating charged particles to high energy comprising means defining a closed region for acceleration of charged particles along curved paths, field generating means for establishing a time-varying magnetic field in said region transverse to said paths, means including electrodes adjacent said paths and an oscillator having a constant frequency connected thereto for repeatedly accelerating charged particles along said paths, and modulating means cooperating with said field generating means for effectively energizing said electrodes with the output of said oscillator while the strength of said magnetic field is low and for effectively de-energizing said electrodes when the strength of said magnetic field is high.

8. Apparatus for accelerating charged particles to high energy comprising means defining a closed region for acceleration of charged particles along curved paths, field generating means for establishing a time-varying magnetic field in said region transverse to said paths, means including electrodes adjacent said paths and an oscillator having a constant frequency connected thereto for repeatedly accelerating charged particles along said paths, modulating means cooperating with said field generating means for effectively energizing said electrodes with the output of said oscillator while the strength of said magnetic field is low and for effectively de-energizing said electrodes when the strength of said magnetic field is high, and means also cooperating with said field generating means for injecting charged particles tangentially into said region while said electrodes are energized.

9. Apparatus for generating and utilizing charged particles of high energy comprising means defining a closed region for acceleration of charged particles along curved paths, field generating means for establishing a time-varying magnetic field in said region transverse to said paths, means including electrodes adjacent said paths and a constant frequency oscillator connected thereto for repeatedly applying electric impulses to charged particles along said paths, modulating means cooperating with said field generating means for effectively energizing said electrodes with the output from said oscillator while the strength of said magnetic field is low and for effectively de-energizing said electrodes when the strength of said magnetic field is high whereby the particles attain high energy, a target disposed in said region, and means for altering the strength of said magnetic field after the particles have attained high energy, whereby the highly energized particles impinge upon said target.

10. Apparatus for generating and utilizing charged particles of high energy comprising means defining a closed region for acceleration of charged particles along curved paths, field generating means for establishing a time-varying magnetic field in said region traverse to said paths, means including electrodes adjacent said paths and a constant frequency oscillator connected thereto for repeatedly applying electric impulses to charged particles along said paths, modulating means cooperating with said field generating means for effectively energizing said electrodes with the output of said oscillator while the strength of said magnetic field is low and for effectively de-energizing said electrodes while the strength of said magnetic field is high whereby accelerated charged particles revolve in predetermined orbits at high energy, a target disposed in said region outside said orbits, and means also cooperating with said field generating means for deflecting said particles to said target after they attain high energies.

11. Apparatus for generating and utilizing charged particles to high energies comprising means defining a closed region for acceleration of charged particles along curved paths, means for establishing a time-varying magnetic field in said region transverse to said paths, means including electrodes adjacent said paths and a constant frequency oscillator connected thereto for repeatedly applying electric impulses to charged particles along said paths, modulating means cooperating with said field generating means for effectively energizing said electrodes with the output from said oscillator while the strength of said magnetic field is low and for effectively de-energizing said electrodes when the strength of said magnetic field is of intermediate value whereby accelerated charged particles revolve in predetermined orbits at high energy, a target disposed within said orbits whereby a further increase in the strength of the magnetic field causes

the accelerated particles to impinge upon the target.

12. An electromagnet accelerator comprising a magnetic structure including opposed annular pole pieces defining an annular gap therebetween and also including yokes supporting said pole pieces, said yokes being provided with openings which communicate with the hollow cylindrical space enclosed by said pole pieces, an annular tank disposed in said gap and electrode structure disposed in said tank for creating electric fields tangentially therein, magnetizing windings cooperating with said pole pieces to establish a magnetic field through said gap, an oscillator associated with said electrode structure for establishing oscillating tangential electric fields within said tank, and means for altering the ratio of the strength of said magnetic field to the frequency at which said oscillator operates.

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