

Oct. 18, 1949.

H. C. POLLOCK ET AL

2,485,409

IMPARTING HIGH ENERGY TO CHARGED PARTICLES

Filed Jan. 5, 1946

3 Sheets-Sheet 1

Fig. 1.

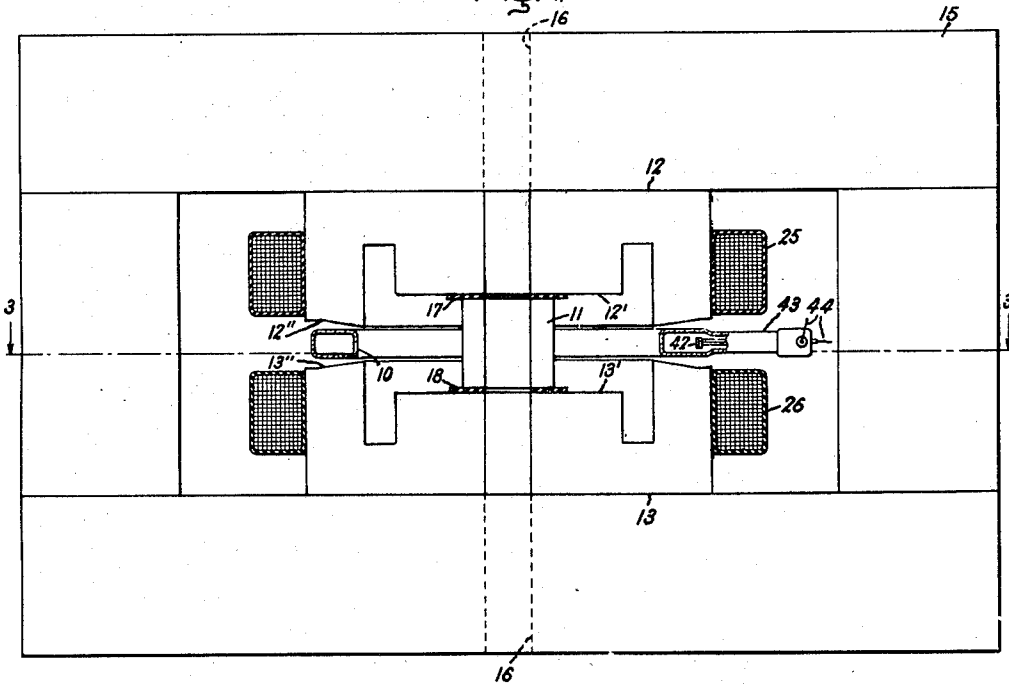
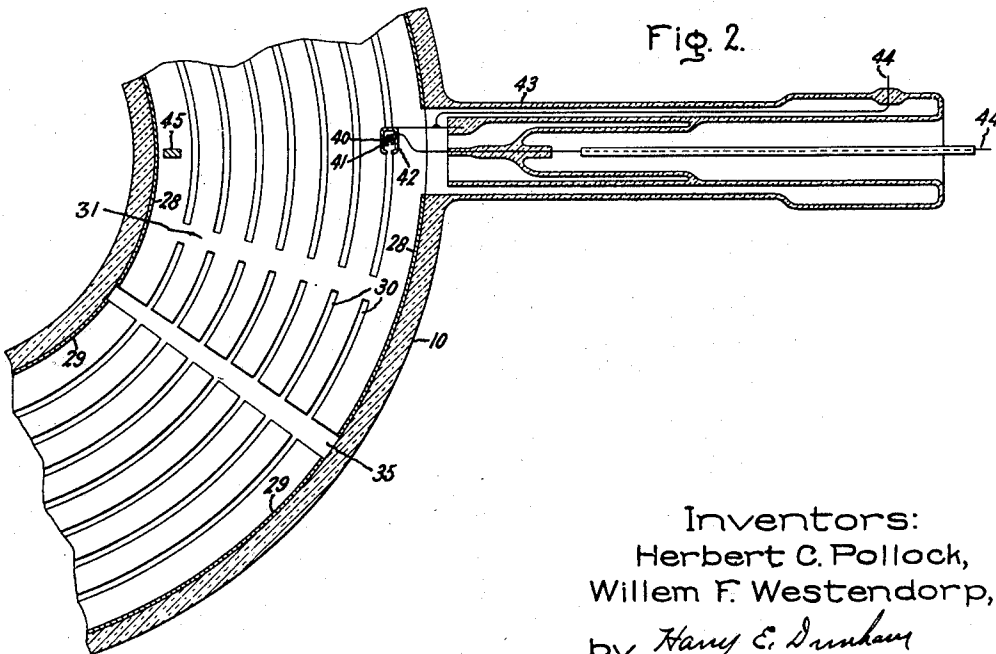


Fig. 2.



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3 Sheets-Sheet 2

Fig. 3.

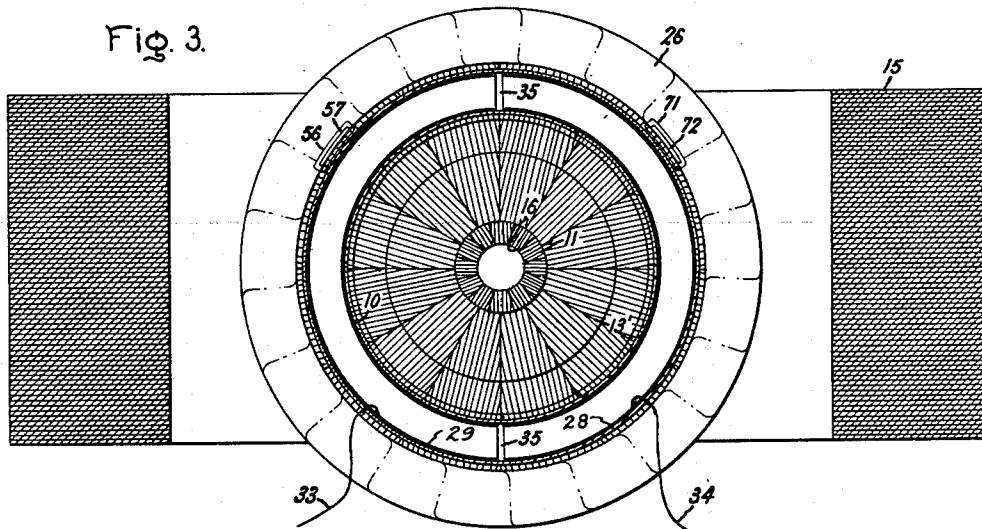
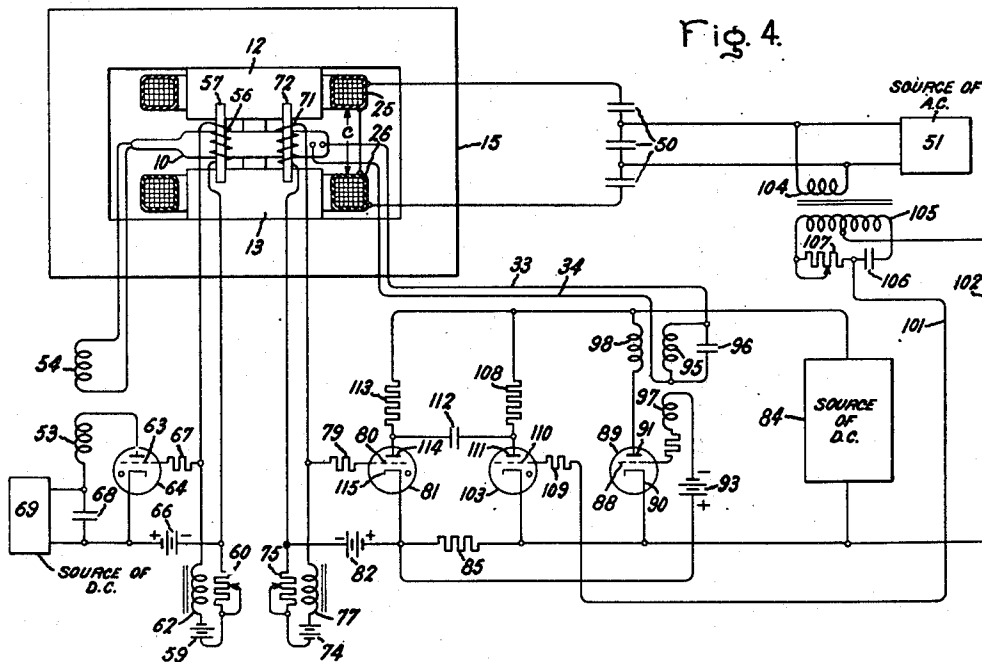


Fig. 4.



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3 Sheets-Sheet 3

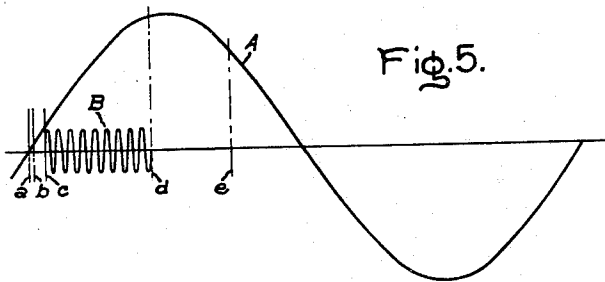


Fig. 5.

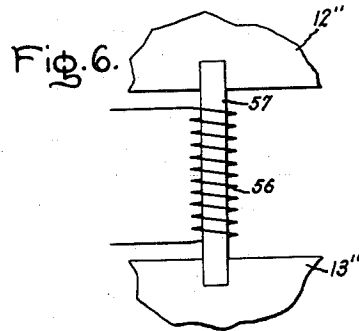


Fig. 6.

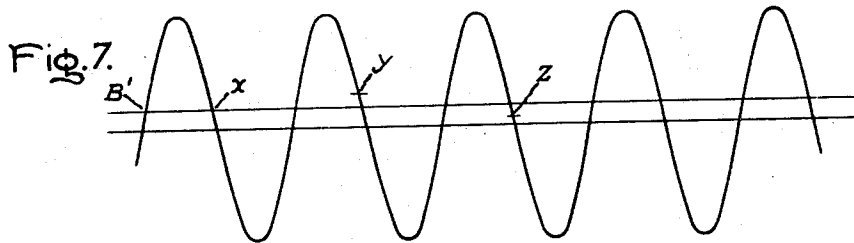


Fig. 7.

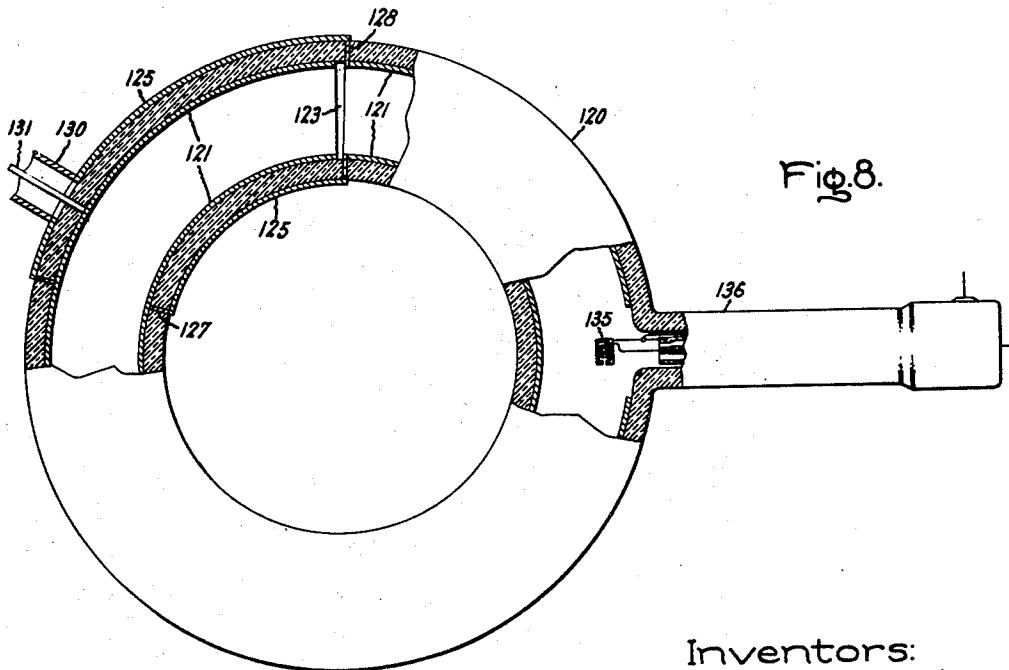


Fig. 8.

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UNITED STATES PATENT OFFICE

2,485,409

IMPARTING HIGH ENERGY TO CHARGED PARTICLES

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Application January 5, 1946, Serial No. 639,462

12 Claims. (Cl. 250-27)

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The present invention relates to methods and means for imparting high energy to charged particles, particularly electrons.

It is known to impart energy on the order of several million electron volts or higher to electrons by the action of a time-varying magnetic field. For example, an apparatus for producing this result is disclosed in U. S. Patent 2,394,071, patented February 5, 1946, in the name of Willem F. Westendorp and assigned to the General Electric Company, a corporation of New York.

It is also known to accelerate ions by the action of a localized electric field acting repeatedly on such ions as they gyrate in a circular or spiral path, an example of this type of equipment being the so-called cyclotron. It has been still further proposed to apply the last-mentioned principle to the acceleration of electrons.

Magnetic acceleration of electrons has been outstandingly successful and electron energies on the order of 100 m. e. v. (million electron volts) have been obtained by this mechanism. However, obtaining energy values of this level or above requires the use of magnetic structures of relatively great weight. Circular acceleration of electrons by the use of localized electric fields, on the other hand, requires an objectionably large chamber for the gyration of the electrons as they accelerate from low velocity to high velocity levels.

It is an object of our present invention to provide an accelerator which is characterized by a low or at least a minimal content of magnetic material and which at the same time requires an accelerating chamber of dimensions readily obtainable in practice.

It is a further object of the invention to provide an accelerator capable in its ultimate embodiments of producing electrons at energy levels materially in excess of 100 m. e. v.

One aspect of the invention consists in the provision of a method and means of imparting high energy to charged particles by subjecting them to the successive action of magnetic and electric fields. In a more specific sense, the invention includes initially accelerating charged particles by the action of a field produced by a time-varying magnetic flux and thereafter producing continued acceleration of such particles by a localized electric field of cyclically varying character.

The features of the invention desired to be protected herein are pointed out with particularity in the appended claims. The invention itself, together with further objects and ad-

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vantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings in which Fig. 1 is a partially sectionalized elevation of an accelerator suitably embodying the invention; Fig. 2 is an enlarged fragmentary section of the discharge vessel shown in Fig. 1; Fig. 3 is a cross section taken on line 3-3 of Fig. 1; Fig. 4 is a schematic representation of excitation equipment useful in connection with the device of Fig. 1; Fig. 5 is a graphical representation helpful in explaining the invention; Fig. 6 is an enlarged detail view of one item of the equipment of Fig. 4; Fig. 7 is a second graphical representation, and Fig. 8 illustrates a practical construction of one feature of the invention.

Referring particularly to Fig. 1, there is shown in section a closed rotationally symmetrical glass vessel 10 which defines within its interior an annular chamber. As will be explained in greater detail at a later point, the vessel 10 provides a circular orbit in which charged particles (e. g., electrons) may be accelerated to a high energy level. The vessel is preferably highly evacuated and is provided on its interior surface with a conductive coating, for example, a layer of silver, which is provided with spaced gaps enabling it to serve as a high frequency electrode system. The details of this electrode system do not appear in Fig. 1 but are illustrated in Fig. 2 which will be described in detail at a later point.

The vessel 10 is supported symmetrically about the axis of a laminated magnetic structure having a central flux path provided by a laminated annular iron core 11. This core is supported at its extremities by attachment to the central portions of opposed pole pieces 12 and 13, which have planar circular areas 12' and 13' and tapered annular areas 12'' and 13''. These pole pieces are in turn supported by a rectangular frame 15 of laminated iron which surrounds and extends transversely to the vessel 10.

The ends of the core 11 are separated from the pole pieces 12 and 13 by narrow, insulation-filled gaps 17 and 18 which are so proportioned as to cause the core to saturate at a predetermined level of the magnetic flux passing through it. The annular faces 12'' and 13'' of the two pole pieces each have a double taper as shown, the purpose of this configuration being explained at a later point herein. An opening 16 which extends continuously through the frame 15, the pole pieces 12 and 13 and the core 11 permits cooling air to be circulated through these parts.

The magnetic structure, which is preferably of

laminated construction throughout, is excited by means of a pair of series-connected coils 25 and 26 which surround the pole pieces 12 and 13 and which may be energized in such a manner as to provide a cyclically varying flux in the magnetic circuit.

Referring now to Fig. 2, which shows additional details concerning the construction of the vessel 10, the interior of the vessel bears high frequency electrodes 28, 29 which comprise a layer of metal (e. g., silver) applied by painting and plating, or otherwise, to the interior surface of the vessel. The coating thus provided is subdivided longitudinally by narrow uncoated areas 30 so as to minimize the circulation of induced electric currents. A solid band of metal 31 provided in connection with each section of the electrode system interconnects the otherwise subdivided segments so that each group of segments functions as a single high frequency electrode. Lead-in conductors 33 and 34 (shown schematically in Fig. 3) are provided for the purpose of conducting high frequency potential to the electrodes just described. By means of these conductors and the electrodes a localized electric field can be established across gaps 35 which separate the extremities of the various electrode segments. In the illustrated arrangement identical gaps are provided at diametrically opposite parts of the discharge vessel as appears more clearly in Fig. 3.

In addition to the high frequency electrode arrangement just described, the vessel 10 contains within the region of influence of the magnetic field produced by the annular pole pieces 12'' and 13'' a thermionic cathode 40 Figure 2 which in connection with associated electrodes 41 and 42 serves to generate a stream of electrons. The electrodes 40-42 are supported by a stem 43 and are supplied with potential and with heating current (in the case of the cathode 40) by lead-in wires 44 sealed into the stem. A target 45, intended under certain conditions to intercept electrons, is supported near the inner periphery of the discharge vessel.

As will be further explained at a later point, means are provided in connection with the coils 25 and 26 for varying the magnetization of the iron core system previously described in connection with Fig. 1. Electrons produced within the discharge vessel 10 are affected in two ways by the variations in magnetic flux thus obtained. In the first place, since the magnetic flux traversing the core 11 links the circular path provided by the vessel 10, any variation of such flux necessarily produces an electric field tending to accelerate electrons projected along such path. In this latter respect the apparatus is comparable to a transformer with a secondary comprising a circular path along which the various electrons are accelerated. In general, although the voltage per turn in such a transformer may be low, within a practically attainable range of flux variation the electrons can be made to achieve very high energies (several million electron volts) because of the tremendous number of turns which they may execute during a single cycle of magnetic flux variation. In addition to the acceleration produced by flux linking the electron path, the flux produced by the annular pole pieces 12'' and 13'' in the region of the electron orbit tends to cause the electrons to follow an inwardly spiraling path. It has been shown that by a proper design of the magnetic structure the centripetal force produced by the magnetic field existing at the electron orbit may be caused to

balance the centrifugal tendencies of the accelerated electrons. In general, this result requires that the following relationship be satisfied:

$$\phi = 2\pi r^2 B_r$$

Where ϕ is the flux included in the electron orbit, r is the radius of the orbit and B_r is the field strength at the orbit. This equation obviously means that the flux ϕ must be twice as strong as that which would be produced by a homogenous field equal to the field B_r extending over the entire area enclosed by the orbital electron path. This condition may be realized by making the reluctance per unit of cross-sectional area of the magnetic path at the electron orbit greater by an appropriate amount than its average reluctance within the orbit. In order to maintain the desired proportionality between the enclosed flux and the guide field (i. e., the field B_r) at all times during an accelerating period, one may adjust the air gap existing between the pole pieces 12'' and 13'' to the appropriate value. It is readily practicable to control the dimensions of the gap from point to point over the pole piece in such a fashion as to effect the balanced relation of guide field and enclosed flux which is desired for the purpose specified above and which is further necessary for radial and axial stability of the electron orbit. This may be done, for example, by a construction such as that shown in Fig. 1 in which the pole pieces are doubly tapered. The principles governing the proper space distribution of the guide flux are more fully set forth in D. W. Kerst U. S. Patent 2,394,070, patented February 5, 1946, and assigned to the General Electric Company, a corporation of New York.

When all the conditions specified in the foregoing are fulfilled, electrons introduced into the chamber 10 in a period when the magnetic field is increasing may be expected to be drawn into the particular orbit in which a balance of centripetal and centrifugal forces exist and to be continuously accelerated along such orbit as long as the magnetic field increases in value. Assuming that the peak value of the magnetic field is sufficiently high, a total energy of the order of several million electron volts may be acquired by the accelerated electrons in a small fraction of a second. If it were practical to construct a magnetic system of any desired size, it would be possible in theory to continue indefinitely the acceleration of electrons without incurring limitations imposed by saturation of the iron circuit. However, from a practical viewpoint the weight of iron required to produce by this means electrons of 1000 m. e. v. energy level would be essentially prohibitive, and even at lower energy levels the weight of iron required may be so great as to be objectionable.

The present invention is concerned with the provision of means by which electron acceleration can be carried to a very high level without incurring the need for an excessive mass of iron in the magnetic system.

In the attainment of this result we make use of the possibility of continuing within a relatively fixed orbit by the action of localized electric fields the acceleration of electrons which by other means (specifically, magnetic acceleration) have been brought to a velocity approaching that of light.

In this connection it may be pointed out that when an electron has obtained a velocity corresponding to an energy level of about 3 m. e. v. it is already within about 1% of the velocity of light.

Further gains in energy result primarily in an increase in the mass of the affected electrons and only insignificantly in a further gain in electron velocity, this result being consistent with the Einstein mass-energy equivalence formula. Accordingly, electrons which have attained a velocity within a few percent of the velocity of light will gyrate with a relatively constant periodicity provided they can be confined to an orbit of relatively fixed radius. Otherwise expressed, this means that electrons which can be confined to a relatively fixed orbit will traverse such orbit with substantially the same time interval required for each such traversal. It should be noted, however, that this proposition holds only for electrons which have already attained high velocity and that the possibility of securing a fixed time for orbital traversal for electrons starting from rest or from a low velocity presupposes the provision of an expanding or spiral path so that each traversal can occur along a path of materially greater circumference. Therefore, the construction of an accelerating system wholly dependent upon the action of localized electric fields would require the provision of a vacuum chamber of objectionably great volumetric content.

This difficulty is avoided, concurrently with the avoidance of an excessive mass of magnetic material, by combining the principles of magnetic and electric acceleration. The basic structure necessary for this purpose has already been described. It is additionally necessary, however, to specify in greater detail the nature of the exciting means employed with such a structure. One example of a suitable excitation system is that exemplified in Fig. 4. In this figure excitation of the magnetic circuit is provided by the two coils 25 and 26 connected in series and placed in circuit with a capacitor bank 50 and with an alternating-current power source 51. It is the function of the power source, which may suitably be a 60-cycle supply, to produce cyclical variations of the magnetic fields of the accelerator to permit successively injected groups of electrons to be accelerated thereby.

As previously explained, electrons are introduced into the vacuum vessel 10 by means of an electron gun (see Fig. 2). The electrodes 40 and 42 of this gun are included in the secondary circuit of a pulse transformer having a primary 53 and a secondary 54 (Fig. 4) which serves to apply a pulse of short duration between such electrodes.

The desired timing of the voltage pulse applied to the electron injecting electrodes with respect to the variations of the magnetic field produced by the coils 25 and 26 is indicated in Fig. 5. Referring to this figure, it is to be assumed that curve A represents the variations of the magnetic flux. At time *a*, the alternating current flux density passes through zero. At time *b*, a few microseconds later, the field has the proper value to match the electron velocity which would be produced by application of the voltage pulse from transformer 53, 54 to the electron injecting electrodes. Energization of the injecting electrodes at this point is obtained by means of a voltage pulse derived from a winding 56 provided on a small core 57 of high permeability ferromagnetic material supported across the gap between the outer surfaces of the pole pieces 12 and 13. The details of this core and winding are illustrated in Fig. 6. A biasing flux may be produced in the core by means of a direct current supplied to the coil by a direct current source indicated diagrammatically as a battery 59. A variable resistor

59 connected in series with the source permits adjustment of the bias thus established. The winding 56 will produce a voltage pulse when the flux through the high permeability core reverses, the timing of this event being determined jointly by the variations in flux between the pole pieces 12'' and 13'' and by the effect of the biasing current supplied by the source 59. A choke coil 62 in series with the battery 59 prevents the voltage pulse referred to from being short-circuited by the battery. The pulse is applied to the grid 63 of a thyratron tube 64 (controlled gaseous rectifier) having its grid normally biased negative by a battery 66 which connects with the grid through the winding 56 and a resistor 67. The resulting conductivity of the tube 64 discharges a capacitor 68 through the primary winding 53 of the pulse transformer, leading to an abrupt injection of electrons into the discharge vessel 10. A source of direct current indicated diagrammatically at 69 serves to maintain the capacitor 68 in normally charged condition. An alternative method of securing adjustable timing of electron injection involves the use of 25 multivibrator circuits.

If the introduction of electrons into the vessel 10 is properly correlated with the changed magnitude of the magnetic flux produced by the coils 25 and 26 as explained in connection with the description of Fig. 5, an appreciable portion of such electrons will be captured in a circular path paralleling the circumference of the chamber 10. They will be accelerated along this path by the electric field associated with the rate of change of the magnetic flux through the orbit and will be maintained in a stable orbit by the effect of the guide field produced by the pole pieces 12'' and 13''.

Referring again to Fig. 5, acceleration of the electrons by the mechanism just described will continue up to a point *c* at which saturation of the central magnetic core 11 is assumed to occur (i. e., as a result of the designed saturation characteristic of the core 11). Before or at the time the point *c* is reached, however, a new process of electron acceleration is introduced. At time *c*, which may be several hundred microseconds later than *b*, the electrons may be assumed to have reached a velocity within one percent (1%) or less of the velocity of light, this degree of acceleration being readily obtainable by the magnetic means above described. Assuming that the magnetic guide field continues to hold the electrons to a circle of fixed diameter, they will move around such circle at substantially constant frequency. This fact permits their energy to be further increased in correlation with the continuing increase in the strength of the guide field by applying to the accelerating high frequency electrodes 28 and 29 (Fig. 3) an electric field which reverses at a frequency corresponding to the frequency of rotation of the electrons. The generation and timing of this high frequency field form the remaining subject matter of Fig. 4.

In this figure a voltage for timing the initiation of the high frequency excitation is provided by a winding 71 on a core 72 of high permeability ferromagnetic material bridging the gap between the pole pieces 20 and 21. The winding 71 is subjected to a direct current bias obtained from a direct current source 74 and regulated by means of a variable resistor 75. The bias is in such direction as to produce a magnetomotive force opposed to that created by the coils 25 and 26 during the accelerating part of operating cycle,

hence a reversal of flux will occur when the strength of the latter magnetomotive force exceeds that produced by the direct-current bias. The time of such reversal is obviously a function of the magnitude of the bias. Depending upon the magnitude of the bias thus supplied, the winding 71 will, upon reversal of its net flux as controlled by variations of the magnetic field in the gap between pole pieces 12 and 13, produce a voltage pulse, for example, at the time *c* (Fig. 5). A choke coil 77 in series with the direct current source 74 offers a high impedance and keeps the circuit provided through the direct current source from short-circuiting the voltage pulse supplied by the winding 71.

The pulse voltage developed by the winding 71 is applied in a positive sense through a resistor 79 to grid 80 of a thyatron 81, such grid being normally biased to cut-off by a battery 82. This permits current flow from a direct current source 84 through a resistor 85 connected between the cathode of the thyatron 81 and the D.-C. source. The voltage drop thus developed across the resistor supplies a positive bias to the grid 88 of a high vacuum power oscillator tube 89, exemplified as a triode having a cathode 90 and an anode 91 in addition to the grid 88. The grid 88 is normally biased negatively by means of a battery 93. The tank circuit, of the oscillator tube is provided by the combination of an inductance 95 and a capacitance 96 and the grid and plate circuits of the oscillator are coupled to the tank circuit by means of coils 97 and 98 respectively. Under these circumstances a sustained radio frequency oscillation may be set up at a frequency determined by the tuning of the tank circuit, and the voltage thus developed across the circuit may be applied through conductors 33 and 34 to the accelerating electrodes 28 and 29 (compare Fig. 3). The tank circuit should, of course, be adjustable to permit a voltage of the desired frequency to be obtained, for example, a frequency of the order of ten to one hundred megacycles. (See below for a discussion of the factors determining the proper tank frequency.)

Referring again to Fig. 5, the radio frequency voltage initiated at time *c* by the means just described is indicated conventionally by the sinusoidal curve B. Assuming the frequency of this voltage to be the same as or a harmonic of the orbital frequency of the electrons circulating in the discharge vessel 10, continued acceleration of such electrons will occur as they traverse the interelectrode gaps 35. By this means the electrons may be brought to relatively very high energy levels. When the application of high frequency potential to the electrodes is stopped, for example, at the point *d*, the accelerated electrons will continue to move without further change in energy level. However, assuming that the point *d* is attained at a time when the magnetic flux between the pole pieces 12' and 13' is continuing to increase, the path of the electrons will become an inwardly spiraling one. As a result, the electrons will eventually impinge upon the target 45 (Fig. 2) which, as previously described, is located near the inner circumference of the chamber 10. The interception of electrons under these circumstances results in the production of X-rays or other radiations of high energy level.

As a possible alternative, interception of the accelerated electrons may be accomplished by continuing the application of the radio frequency potential B until a time *e* beyond the crest of the flux wave A. Under these circumstances, dis-

continuation of the radio frequency potential will cause an outward spiraling of the electrons due to the progressive weakening of the magnetic guide field. Such electrons may then be intercepted by the electron gun part 42 or by a target provided in proximity thereto.

Termination of the radio frequency oscillations generated by the tube 89 and its associated circuits is accomplished by firing a thyatron tube 103 (Fig. 4), for example, by means of a conventional resistance-capacity network shown as including a transformer winding 105, a capacitor 106, and a resistor 107, the latter being variable by means of an adjustable shunt.

The winding 105 is coupled to a primary winding 104 which in turn is connected to the primary alternating current power source 51. Conductors 101 and 102 respectively connected to the midpoint of the winding 105 and to a terminal between capacitor 106 and resistor 107 permit taking off a sinusoidal voltage, the phase of which can be varied by adjustment of the resistor shunt. This voltage is applied through a resistor 109 to the grid 110 of the tube 103 in such a sense as to cause the tube to fire at an instant corresponding to the desired time of termination of the oscillations generated by tube 89. The firing of the thyatron tube 103 through the loading resistor 108 causes a sudden drop in the potential of its anode 111. This results in a flow of current through the circuit which includes a condenser 112 and a commutating resistor 113 in series with the anode 114 of the tube 81. The potential of the anode 114 is thus brought below the value necessary to sustain conductivity of the tube 81, resulting in cessation of current flow through the tube. The attendant discontinuance of current flow through the resistor 85 causes the oscillator tube 89 to return to its biased-off or non-oscillatory condition.

The operating cycle which has been described in the foregoing may be automatically repeated for each positive loop of the flux wave A (Fig. 5) thus resulting in the repetitive production of groups of high energy electrons. Reviewing the operation of the equipment from a quantitative viewpoint, it is considered desirable to maintain the period of magnetic acceleration of electrons through a period sufficient to raise the energy level of the electrons to from 2 to 5 m. e. v., since the velocity of electrons within this energy range is within one percent (1%) of the velocity of light. Magnetic acceleration to much higher energy levels is readily possible but at the expense of increasing the size of the magnetic circuit required, hence, there are very significant advantages in transferring to acceleration by the high frequency electrode system at this point.

It is practical and expedient to design the equipment so that the acceleration received by the rotating electrons will be from 100 volts to several thousand volts for each orbital traversal, the exact value to be selected depending upon the ultimate velocity desired to be obtained, and being directly governed by the rate of change of the magnetic field. The figures given apply both to the loop voltage developed by the changing magnetic flux initially produced within the region linking the electron orbit and to the voltage developed between the electrodes 28 and 29 (Fig. 3) during the period when acceleration is dependent upon these electrodes.

The frequency of reversal of the potential applied between the electrodes 28 and 29 is determined directly by the circumference of the elec-

tron orbit (which, of course, corresponds approximately to the mean circumference of the discharge chamber 10) divided into the velocity of light. Thus, an orbit diameter of 66 inches indicates a frequency of approximately 57 megacycles. Such frequencies can be readily developed at adequate power levels in various ways as, for example, by the use of high frequency triodes (as in Fig. 4) or by tetrodes or other suitable tubes. In certain instances, especially where extremely high frequencies are desirable, it may be advisable to use a magnetron as a power source. In any event, however, the source selected should be adapted to produce potential variations of constant frequency since this is essential to the satisfactory operation of the equipment.

It is found that no precise correlation of the rate of increase of the magnetic guide field with the cyclical variations of the high frequency electric field need be maintained since the system is inherently self-synchronizing in accordance with the following analysis.

Refer, for example, to the curve B' of Fig. 7 which represents to an expanded scale the electric field B of Fig. 5. Assume that the optimum energy increment from the standpoint of maintaining correlation with the rate of increase of the guide field is that imparted by an electric field corresponding to point x on curve B'.

Consider an electron which traverses the gap at an instant when the field strength is at the level indicated at y. Under these circumstances the energy gained by the electron will obviously be somewhat excessive compared with the value predicated as optimum for correlation with the guide field at its then existing level. Consequently, the excess momentum involved will cause the electron to move slightly in the outward direction so that the circumference of its orbital path will be increased. Since, under the conditions assumed, the electrons possess essentially constant velocity, the time required for traversal of the orbital path will thus be correspondingly increased and the electron may, therefore, make its next arrival at the inter-electrode gap at a point corresponding to z. Under these circumstances too little energy will be absorbed and an inward movement of the electron orbit will result, thus again decreasing the transit time. Either with this adjustment or with some subsequent adjustment of velocity the electron will finally reach a condition at which it repeatedly traverses the gap in time to experience the optimum field strength x. This experience will be repeated for the various electrons making up the total electron stream, so that these electrons will in due course become bunched in a group traversing the accelerating path at a relatively fixed (or very slowly expanding) orbit and at a definite periodicity identical with that of the high frequency potential by which the electrodes are excited.

The high frequency electrode system described in the foregoing is of a more elementary character than would be employed in a practical embodiment of the invention, and in Fig. 8 there is shown a more elaborate system, useful particularly at high operating frequencies. The details of this construction are the separate invention of Anatole Gurewitsch and are claimed by him in his application Serial No. 691,293, filed August 17, 1946, and assigned to the General Electric Company, being shown herein for the pur-

pose of illustrating one typical adaptation of the invention.

Referring to Fig. 8, there is shown an annular glass vessel 120, preferably highly evacuated, which is provided on its inner surface with a conductive metallic coating 121 consisting, for example, of silver. This coating may be longitudinally subdivided in the manner described in connection with Fig. 2 hereof and in any event is provided with a gap at 123 across which a high frequency electric field may be established.

On the outside of the discharge vessel there is provided a second conductive metal coating 125 which extends over only a portion of the vessel. Coating 125 is electrically connected to the inner coating 121 by two metal rings 127 and 128 sealed into the wall of the discharge vessel. It is to be noted that the ring 128 connects directly with the portion of the coating 121 which forms the right-hand boundary of the gap 123 while the ring 127 is connected to the coating 121 at a point which is to the left of the gap 123 and appreciably spaced therefrom. Actually, the spacing of the ring 127 with reference to the gap 123 is chosen to be approximately a quarter wave length at the desired frequency of the field to be established across the gap 123. (Some discrepancy will necessarily exist between the length actually employed and an exact quarter wave length in order to compensate for the capacity of the gap and for the dielectric properties of the glass wall of the discharge vessel interposed between the conductors 121 and 125.)

With the correct selection of dimensions, the space between the conductors 121 and 125 constitutes in effect a quarter wave concentric transmission line section. Accordingly, if the structure thus provided is excited at the proper frequency, a cyclically reversible electric field of high intensity may be made to appear across the gap 123.

In the arrangement illustrated, excitation of the transmission line section is accomplished through a concentric conductor transmission line formed by the combination of a metal cylinder 130 which attaches to the conductive layer 125 and by an inner conductor 131 which extends through the wall of the discharge vessel 120 to contact with the inner conductive layer 121. The conductors 130 and 131 are assumed to connect at their remote extremities with a high frequency power source (not shown). The point of attachment of these conductors to the conductors 121 and 125 is chosen in such fashion as to match the impedance of the input system to that of the gap 123.

With the arrangement as so far described, it is evident that the conductive coating 125 is not required to be extended over the entire circumference of the discharge vessel 120. However, the inner coating 121 should be essentially coextensive with the inner surface of the vessel in order to provide shielding and to prevent charging of the vessel walls.

It is obviously possible to employ two electrode systems such as that described in Fig. 8 operated in synchronism from a common power source and having their respective gaps located at opposite ends of a diameter of the discharge vessel. Furthermore, a half wave transmission line or a cavity resonator which is resonant at the desired operating frequency might be employed in lieu of the quarter wave system illustrated.

Electrode systems of the character just des-

cribed may be used in accordance with principles previously described herein to produce repeated acceleration of electrons circulating within the vessel 120. Such electrons may be introduced into the vessel by means of an electrode system 135 supported from a stem 136.

It will be understood that the basic principles described herein may, under proper conditions, be used for the acceleration of charged particles other than electrons, for example, for the acceleration of positive ions.

While our invention has been described by reference to particular embodiments thereof, alternative constructions will readily occur to those skilled in the art. We, therefore, aim in the appended claims to cover all such equivalent embodiments as may be within the true spirit and scope of the foregoing description.

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

1. The method of imparting high energy to charged particles which comprises initially accelerating such particles along an orbital path by the action of a time-varying magnetic flux linking said path and thereafter additionally accelerating said particles by the intermittent action of an electric field acting at a selected portion of said path.

2. The method which comprises initially accelerating charged particles along an orbital path by the action of a time-varying magnetic flux linking said path and thereafter additionally accelerating said particles by a localized electric field acting at a selected portion of said path, meanwhile confining said electrons to said path by production of a time-varying magnetic guide field.

3. Apparatus for accelerating charged particles including a source of such particles, a vessel providing an orbital path for particles from said source, a magnetic system effective for a predetermined period to produce a time-varying magnetic flux which links said path, thereby to effect initial acceleration of said particles, means for maintaining said particles within a desired orbit in spite of their changing velocity, and a high frequency system operative after the expiration of said predetermined period to produce an intermittent electric field acting on said particles to effect additional acceleration thereof.

4. Apparatus for accelerating charged particles including a source of such particles, means providing a closed orbital path for particles from said source, a magnetic system for producing a magnetic flux which links said path and which varies with time at a sufficient rate to produce appreciable acceleration of said particles, a magnetic structure complementary to said last-named means for producing a time-varying magnetic field acting on said particles to maintain them within a desired orbit in spite of their varying velocity, and a high frequency system for producing an electric field acting on said particles to produce acceleration thereof supplementary to that produced by the action of said magnetic flux.

5. Apparatus for accelerating charged particles including means for projecting such particles along a reentrant path, a magnetic system effective for a predetermined period to produce a time-varying magnetic field linking said path thereby to cause initial acceleration of said particles, a high frequency system operative at the end of said predetermined period to produce a cyclical electric field acting on said particles at a selected portion of said path thereby to cause additional

acceleration of said particles, and a magnetic structure operative for producing throughout the entire accelerating period a time-varying magnetic field correlated to said first magnetic field and of such space distribution as to maintain said particles within a desired orbit in spite of their varying velocity.

6. Apparatus for accelerating charged particles including means for projecting such particles along a reentrant path, means providing a saturable magnetic circuit linking said path, a low frequency source of excitation for producing a magnetic flux through said circuit which increases continuously until saturation of the circuit occurs and which thereafter effectively ceases to increase whereby said particles are accelerated by the variations of said magnetic flux only prior to saturation of said circuit, a high frequency system operative upon saturation of said magnetic circuit to produce a cyclically varying electric field acting upon a localized region of said re-entrant path, thereby to produce continued acceleration of said particles after cessation of the acceleration due to said magnetic flux, and means for maintaining said particles within a desired orbit in spite of their variations in velocity.

7. Apparatus for accelerating charged particles including means for projecting such particles along a reentrant path, a magnetic circuit linking said path, a source of excitation for producing a time-varying magnetomotive force acting on said circuit, thereby to accelerate said particles by the field produced by the resultant variation in flux through said circuit, a high frequency electrode system effective when energized to produce a localized electric field which causes additional acceleration of said charged particles, and means responsive to attainment of a predetermined value of said magnetomotive force to initiate energization of said electrode system.

8. The method which comprises initially accelerating electrons along an orbital path by the action of a time-varying magnetic flux linking said path while confining said electrons to said path by a concurrently varying magnetic guide field traversing the locus of said path, continuing such initial acceleration until the electrons have attained an energy level of several million electron volts and essentially constant velocity, and thereafter additionally accelerating said electrons by a localized high frequency electric field acting along said path and synchronized in frequency with the frequency of orbital gyration of said electrons, meanwhile continuing the variation of said magnetic guide field to retain the electrons in said path.

9. Apparatus for accelerating charged particles including a particle source for projecting such particles along a re-entrant path, a magnetic structure providing a magnetic circuit linking said path, an exciting system coupled with said magnetic structure to produce a time-varying magnetomotive force acting on said circuit, thereby to accelerate said particles by the field produced by the resultant variation in flux through said circuit, an electrode system in proximity to said path and effective when energized to produce a localized electric field which causes additional acceleration of said charged particles, and means responsive to attainment of a predetermined value of said magnetomotive force to initiate energization of said electrode system.

10. Apparatus for accelerating charged particles including a particle source for projecting such particles along a re-entrant path, a magnetic as-

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sembly having a polar structure which provides a magnetic circuit linking said path and which further provides a magnetic circuit traversing the locus of said path, a low frequency excitation source coupled with said magnetic assembly for producing synchronized time-varying fluxes through said magnetic circuits, the flux through said first circuit inductively accelerating said particles along said path and the field corresponding to said second flux retaining said particles in said path, a high frequency electrode system adjacent said path and effective when energized to produce a localized electric field acting along the path to cause cyclical acceleration of said particles, a high frequency source for exciting said electrodes and a switching circuit responsive to attainment of a selected value of said magnetic fluxes for causing said source to excite said electrodes after a predetermined initial acceleration of said particles by the flux through said first magnetic circuit.

11. In particle-accelerating apparatus of the type in which a circularly symmetrical space- and time-varying magnetic guide field serves to confine charged particles to a fixed orbit irrespective of progressive changes in the kinetic energy of said particles, the combination which includes a magnetic assembly having polar structure and exciting coils coupled therewith for establishing the guide field, further polar structure coupled with said exciting coils for producing a time-varying magnetic flux through said fixed orbit, thereby initially to accelerate said particles around said orbit, high frequency electrode structure embracing said orbit, a source of high frequency excitation for said electrode structure, said structure having a region across which electric fields developed during excitation of the structure are concentrated along a portion of said orbit to produce cumulative acceleration of particles traversing the structure, and a switching circuit having an element responsive to attainment of a predetermined value of the excitation of said magnetic assembly to initiate excitation of said electrode structure by said high frequency source.

12. In particle-accelerating apparatus of the

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type in which a circularly symmetrical space- and time-varying magnetic guide field serves to confine charged particles to a fixed orbit irrespective of progressive changes in the kinetic energy of such particles, the combination which includes a magnetic assembly having polar structure and exciting coils coupled therewith for establishing the guide field, further polar structure coupled with said exciting coils for producing a time-varying magnetic flux through said orbit, thereby initially to accelerate said particles around said orbit, said further polar structure defining a magnetic circuit which is saturable independently of said guide field structure, high frequency electrode structure adjacent said orbit having a region across which is to be produced an electric field acting along said orbit to cause cumulative acceleration of said particles, a high frequency source for exciting said structure to produce a cyclically varying field across said region, a switching circuit operative approximately at the point of saturation of said magnetic flux circuit to initiate excitation of said electrode structure by said high frequency source, whereby cessation of acceleration of said particles by said flux is approximately concurrent with initiation of acceleration of such particles by said electrode structure, and means to intercept the accelerated particles upon disturbance of the equilibrium between the centripetal forces exerted upon the particles by said guide field and the centrifugal forces attributable to their kinetic energy.

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Certificate of Correction

Patent No. 2,485,409

October 18, 1949

HERBERT C. POLLOCK ET AL.

It is hereby certified that errors appear in the printed specification of the above numbered patent requiring correction as follows:

Column 5, line 70, and column 7, line 9, for "pole pieces 12 and 13" read *pole pieces 12" and 13"*;

and that the said Letters Patent should be read with these corrections therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 23rd day of May, A.D. 1950.

[SEAL]

THOMAS F. MURPHY,
Assistant Commissioner of Patents.

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