

Dec. 14, 1954

D. W. KERST

2,697,167

INDUCTION ACCELERATOR

Filed Nov. 8, 1945

4 Sheets-Sheet 1

Fig. 1.

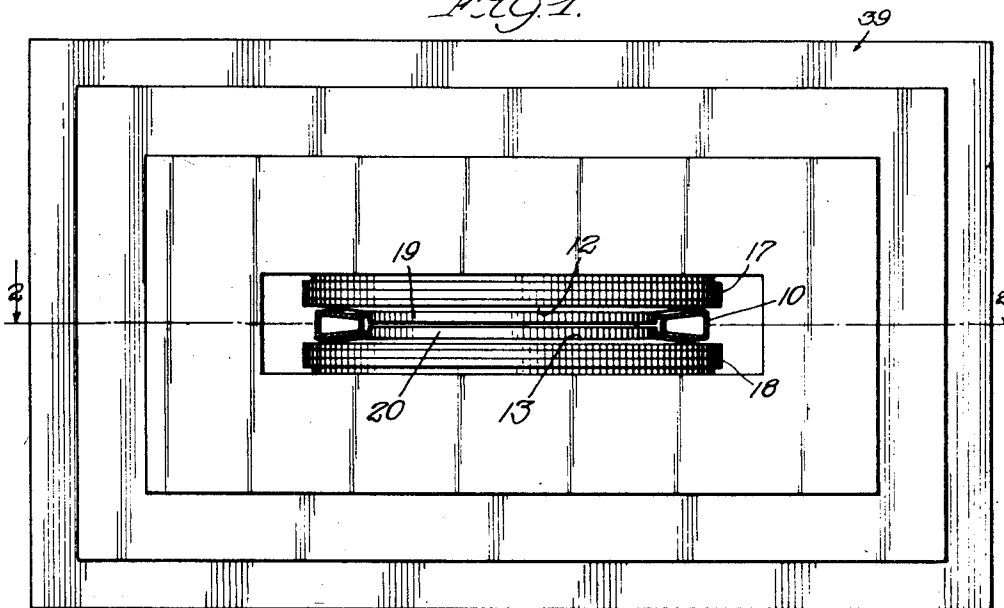


Fig. 2.

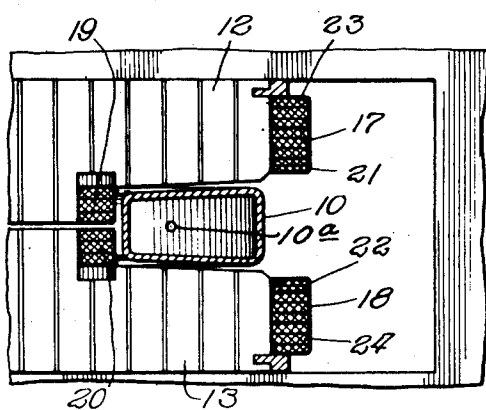
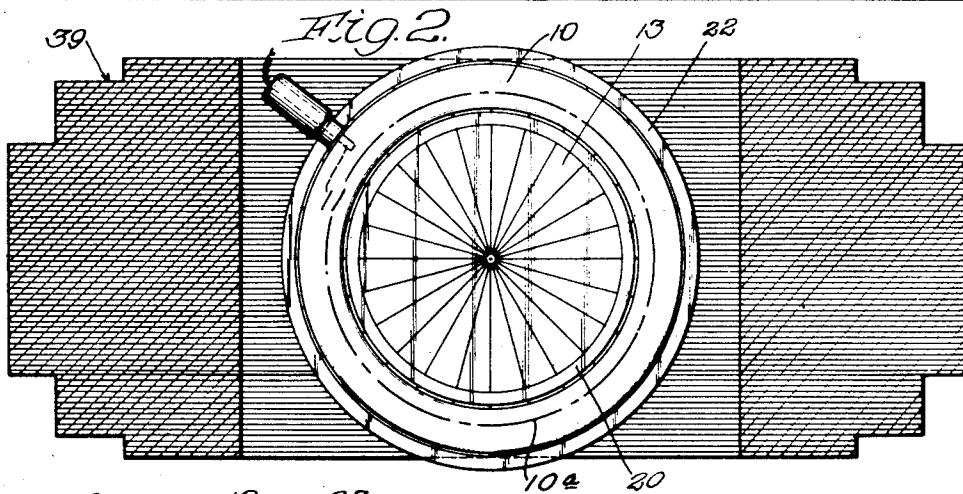


Fig. 3.

Inventor:  
Donald W. Kerst.  
By Clinton, Wild, Schaefer,  
Merriam, Hyman, Att'ys.

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*Fig. 4.*

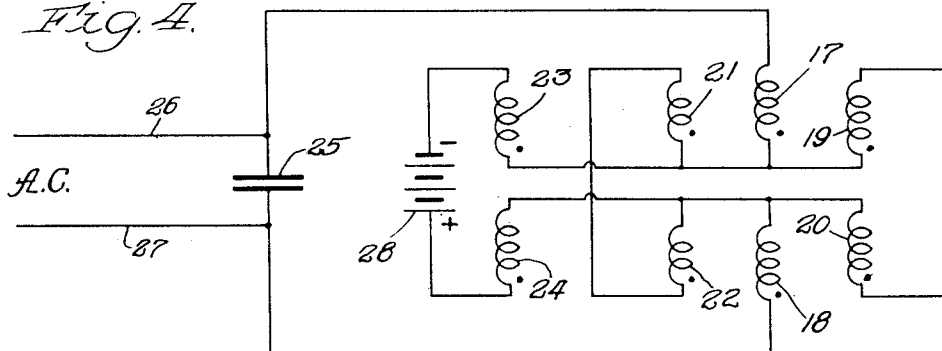


*Fig. 5.*

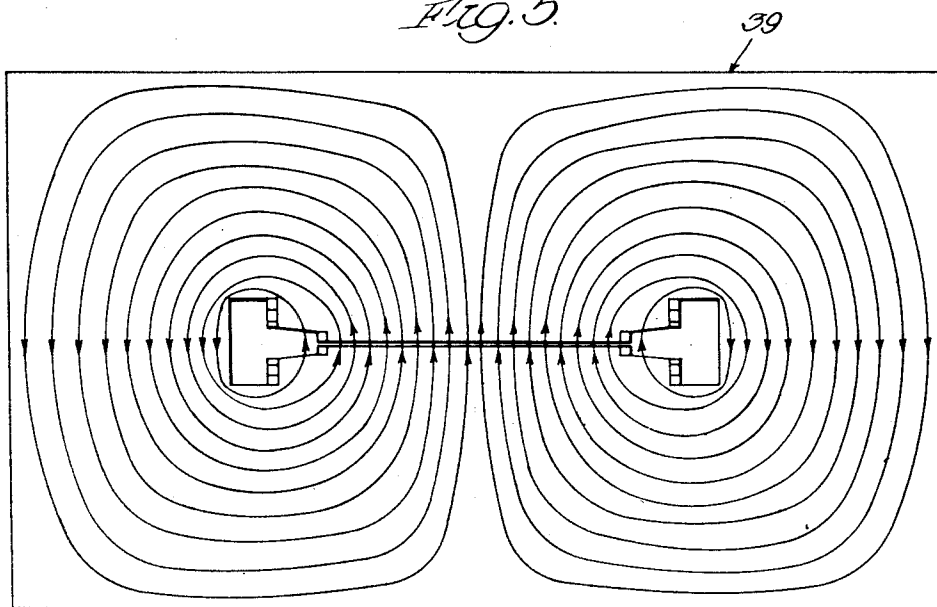
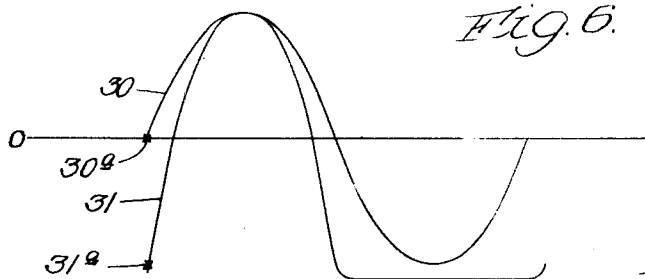


*Fig. 6.*



Inventor:  
Donald W. Kerst,  
By *Charles Wiley Schröder*,  
Meriam, N.Y., Attys.

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D. W. KERST

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Fig. 11.

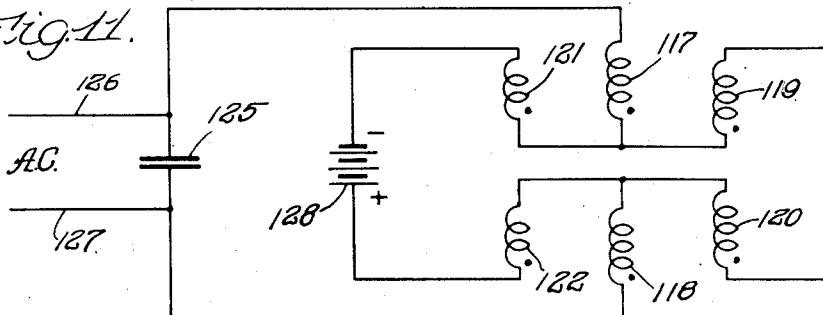


Fig. 12.

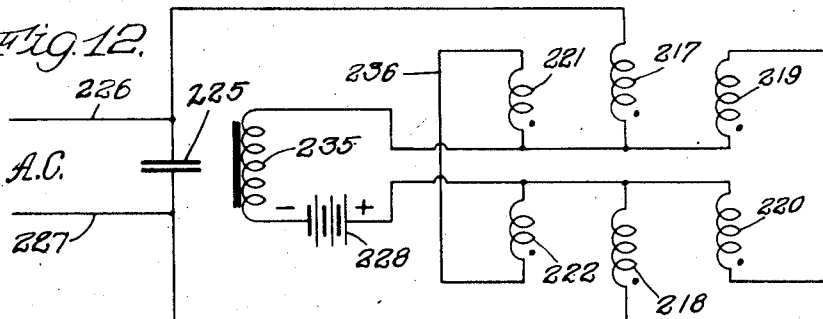


Fig. 13.

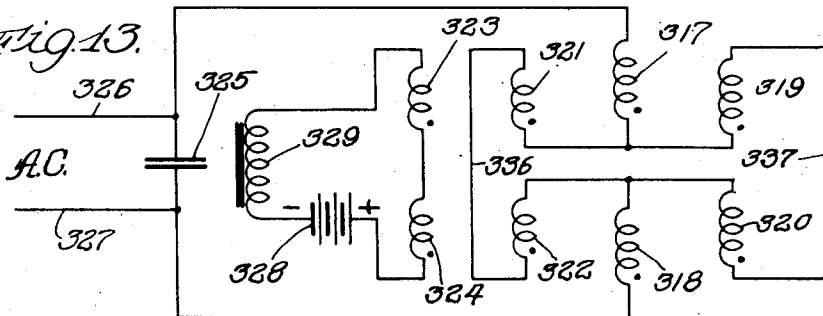
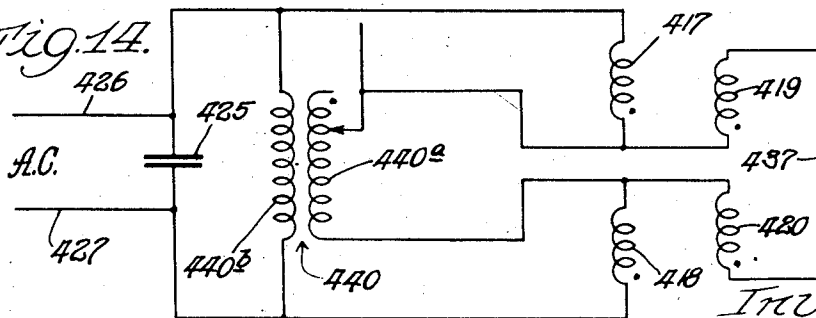


Fig. 14.



Inventor:  
Donald W. Kerst,  
By Chester W. Schroeder,  
Merriam, Hagen, Att'ys.

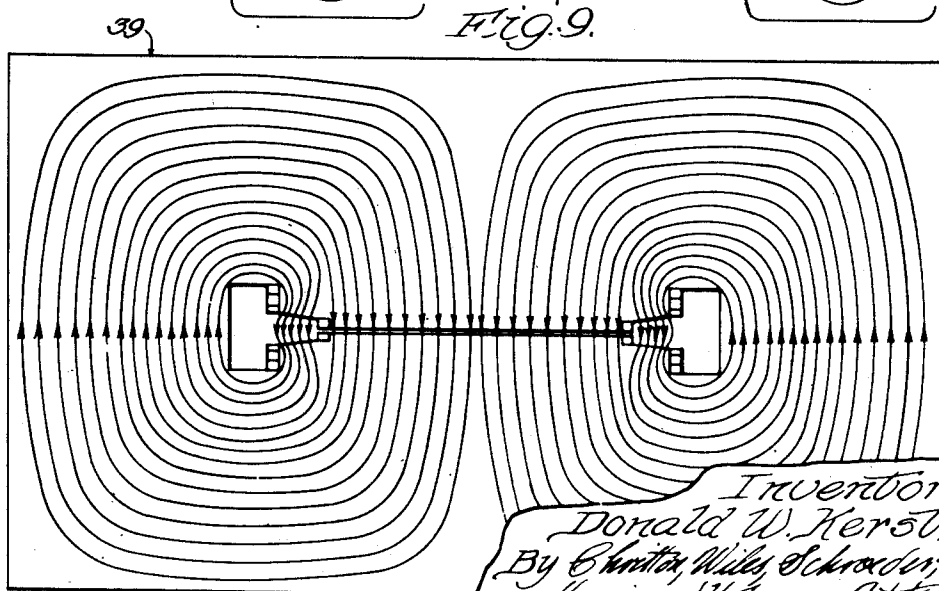
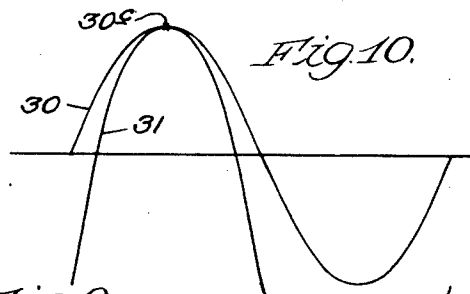
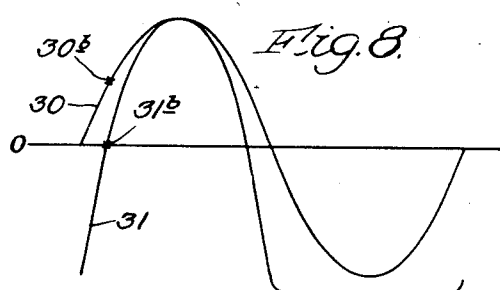
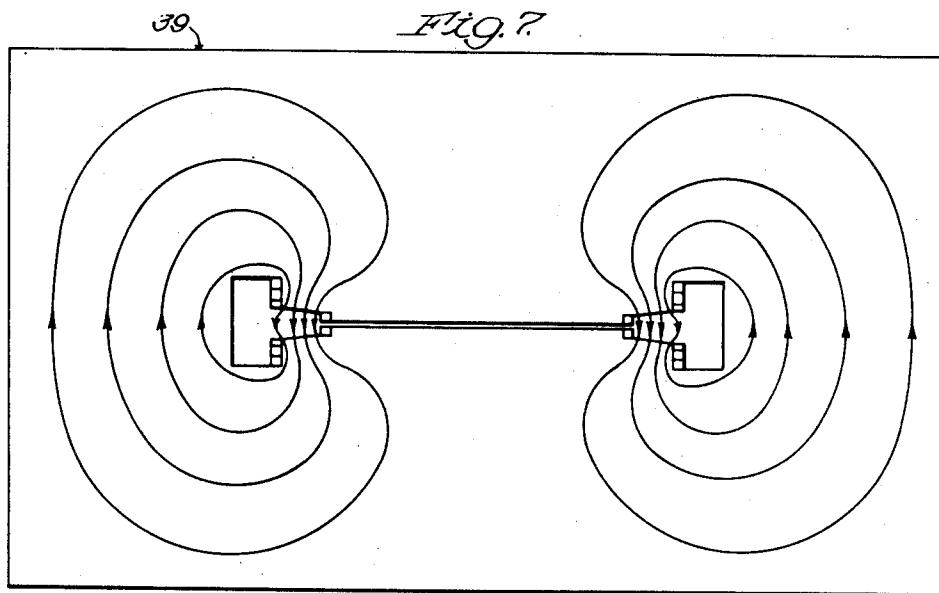
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2,697,167

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4 Sheets-Sheet 4



Inventor:  
Donald W. Kerst,  
By Charles Wiley Schroeder,  
Meriam, Huggins, Fitts.

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2,697,167

## INDUCTION ACCELERATOR

Donald W. Kerst, Champaign, Ill., assignor to The Board of Trustees of The University of Illinois, Urbana, Ill.

Application November 8, 1945, Serial No. 627,481

15 Claims. (Cl. 250—27)

This invention relates to an induction accelerator, and more particularly to means for increasing the efficiency of electron acceleration relative to power consumption, for working at higher maximum flux densities near the orbit or path of the charged particle, for stabilizing the position of the equilibrium orbit, and otherwise improving the apparatus.

This invention relates to magnetic induction accelerator devices which generally comprise an evacuated doughnut-shaped tube, as of glass or porcelain, with means for periodically introducing charged particles, as electrons, into the tube, as a heated filament periodically placed at a high voltage differential with respect to an associated electrode; magnetic means for causing the charged particles to circulate in or near a certain orbit in the tube, generally termed the equilibrium orbit, for a very large number of revolutions, accelerating them continuously during this circulation, this means comprising means for setting up magnetic fields across the orbit and the space within the orbit in certain desired relationships, and for varying the strengths of these fields; and means for utilizing the kinetic energy of the charged particles, as by providing a target which the particles may strike to create X-rays. The circulating charged particle has a centripetal force requirement varying with the radius of its orbit, and field strength relationships are so provided radially as to provide a magnetic holding force also varying as a function of the radius, the equilibrium orbit on or about which the particle travels having a radius where these forces are equal.

The general principles of operation of a magnetic induction accelerator are known to the art and have heretofore been published in various patents and publications, particular reference in this regard being made to Kerst Patent 2,297,305 of September 29, 1942, and an article entitled "The betatron," by D. W. Kerst, which appeared in vol. 10, No. 5, of the American Journal of Physics (October 1942). Magnetic induction accelerators of this type have also been the subject of a number of other patents and publications including the following: Slepian Patent 1,645,304; Steenbeck Patent 2,103,303; Smith Patents 2,143,459 and 2,289,220; Penney Patent 2,193,602; Baldwin Patent 2,331,788; Kerst Patent 2,335,014. Other articles by D. W. Kerst are: "The acceleration of electrons by magnetic induction" which appeared in vol. 60, No. 1, of The Physical Review (July 1, 1941), and "A 20-million electron-volt betatron or induction accelerator" which appeared in vol. 13, No. 9, of The Review of Scientific Instruments (September 1942).

One feature of this invention is that, for a given energy output of the induction accelerator (or betatron, as it is sometimes termed), as in the form of X-rays, a very much smaller magnetic structure and associated parts may be used, with much lower kilo-volt ampere rating or energy input; or, stated in another way, the same magnetic structure (that is, the same amount of iron) and energizing arrangements heretofore used will provide about double the energy output of the betatron in the form of X-rays or other desired manifestations.

One feature which contributes materially to the efficient use of iron in the apparatus is that I have devised and am here disclosing and claiming means whereby the iron or other permeable material of the magnetic structure can be caused to carry, at and near the orbit and near the end of the period of acceleration of the charged particles, flux densities more than double those which

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could heretofore be employed. It has heretofore been necessary to limit the maximum flux density at and near the orbit to about 5,000 gauss in order to permit flux densities near the center to rise to or slightly above double this density. I have found that by starting with what might be termed a negative field near the center of the orbit, and by using a field in the neighborhood of zero near the orbit, I can end the period of acceleration of the charged particles with flux densities approximately equal at the orbit and near the center or both near the working maximum permissible in iron, as 10,000 to 14,000 gauss.

Still another feature of this invention is that means are provided for maintaining desired relationships between changes in field strength in different portions of the magnetic structure despite differences in the shape of the permeability curve of the iron at different flux densities. I achieve this by the use of means for "forcing" the change in flux density in a certain portion of the magnetic structure to keep the desired relationship to change in flux density in another portion, as by the use of two different coils so connected and located relative to the magnetic structure as to cause circulating currents to oppose any deviations from the desired relationships.

Other features and advantages of this invention will be apparent from the following specification and the drawings, in which:

Figure 1 is a side elevational view of an induction accelerator embodying my inventions; Figure 2 is a horizontal sectional view along the line 2—2 of Figure 1; Figure 3 is a fragmentary enlarged sectional view of a portion of the apparatus shown in Figure 1; Figure 4 is a circuit diagram of the apparatus shown in Figures 1—3; Figure 5 is an illustrative flux diagram of apparatus embodying my inventions when the alternating current energizing the apparatus is going through zero; Figure 6 is a diagram of curves representing flux densities at the orbit and at the center of the magnetic structure with "x's" at the points corresponding to the conditions of Figure 5; Figure 7 is an illustrative flux diagram of the same apparatus shown in Figure 5, but when the alternating current has reached half its maximum; Figure 8 is another curve representing field strengths at the orbit and at the center of the magnetic structure, with "x's" at the points corresponding to the condition of Figure 7; Figure 9 is an illustrative flux diagram of the apparatus of Figures 5 and 7 when the alternating current has reached maximum; Figure 10 is a diagram of flux curves with an "x" at the point representing conditions in Figure 9; Figure 11 is a circuit diagram of another arrangement embodying my inventions; Figure 12 is a diagram of still another induction accelerator circuit employing a plurality of coils; Figure 13 is still another representative circuit diagram embodying the inventions being described and claimed here; and Figure 14 is a circuit diagram illustrating the use of a transformer as a flux forcing means.

Inasmuch as the general principles of operation of a magnetic induction accelerator have been fully described in the patents and publications listed above, the description of the general construction and operation of the betatron will be kept brief, and reference may be made to such other publications to supplement this general description if desired.

In the particular embodiment illustrated herewith the tube providing the annular chamber in which the charged particles circulate is here identified as 10, and is provided at one point in its periphery with injector means here identified as 11. The tube is preferably made of porcelain for ease in formation, as is more fully described and claimed in the copending application of Almy and Hursh, Serial No. 596,460, filed May 29, 1945, now abandoned, although it may be made of glass or any other suitable material; and it is preferably coated on the inside with a high resistance conductive coating, as with a very thin film of palladium. The tube is disposed between two generally circular pole pieces here identified as 12 and 13, these pole pieces being shown here as of outwardly tapered or diverging configuration, as may be best seen in Figure 3, although such taper is not necessary, and substantially coaxial with the tube 10, such that the field strength diminishes radially toward the outside of the annular

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chamber, and so that the flux lines curve in a vertical plane to provide the desired vertical stability and damping of vertical oscillations of the charged particles when moving in their circular path. As has been more fully described in the above-mentioned patents, and particularly Kerst Patent 2,297,305, the outwardly tapered configuration of the pole piece faces is such that the magnetic field strength varies inversely with the radial displacement  $r$  according to the proportionality

$$H \propto \frac{1}{r^n}$$

where  $n$  is a constant between zero and unity. This constant has heretofore been preferably kept, by proper design, between .25 and .8, generally in the neighborhood of .75; but neither a tapered pole face configuration nor a design with constants in the range just named is essential, this merely being specified because it comprises the manner in which most betatrons have heretofore been built and has been fully described in patents and articles mentioned earlier. Means for operating efficiently with design constants outside those mentioned immediately above is described and claimed, for example, in the copending Adams application, Serial No. 607,416, which issued as Patent No. 2,473,123 on June 14, 1949.

Surrounding the pole pieces 12 and 13 are the main field producing coils 17 and 18. Surrounding all of the parts just described is a frame structure of iron or other magnetically permeable material completing the magnetic circuit, this comprising top, bottom and side portions and being here identified in general as 39. The magnet coils 17 and 18 are energized by an alternating current of considerable amplitude, these coils preferably being connected in parallel with condensers and energized from an alternating current generator, which may have a frequency of 180 cycles per second and is preferably above the conventional 60 cycles per second, the magnet coil and condenser providing a resonant circuit at this frequency in which high currents circulate, the generator merely providing the actuating current replacing losses in the system. The electron injecting mechanism is intended, as by excitation of a thyatron grid by voltage from a pickup or peaking strip in the field of the main magnet coils, to inject the electrons into the tube at the beginning of the rising quarter cycle of current on the positive side of the cycle. By the electron gun or injector means, the electrons are injected into the tube substantially tangent to the circular path provided, with substantial initial energy of more than several electron volts. This initial energy is preferably of the order of several thousand electron volts; and the injection may be accomplished by structures of the kind shown in the above-mentioned patents and publications, or by an improved structure of the kind disclosed and claimed in my copending Kerst application, Serial No. 617,255, which issued as Patent No. 2,497,891 on February 21, 1950. Coaction between the moving electrons and the vertical lines of force of the magnetic field cause them to be accelerated radially by the magnetic force, inwardly if the injector means is outside of the equilibrium orbit 10a. At the same time, the increasing magnetic field accelerates the electrons in their orbital path. The period of acceleration of speed of electrons continues during the entire rising portion of the positive cycle of the current, as the magnetic field is increasing during this time; and since the electrons may have described several thousand revolutions in this time, strong magnetic fields will have worked their energy up to millions of electron volts. At the end of this time means are used to swing the electrons out of their equilibrium orbit 10a, as by a change in the distribution of magnetic field, into collision with a target, for example. During the time the electrons are describing revolutions in and about the equilibrium orbit, maintenance of the electrons at and near the equilibrium orbit is effected, in the case of radial stability, by proportioning of the field relationships such that the average change of field strength throughout the area within the orbit is double the change of field strength at the orbit; and vertical or axial stability is secured by the curvature of the lines of force in a vertical plane.

Where the injector structure lies to the outside of the equilibrium orbit, as illustrated here, the electrons are injected under conditions such that the radial field strength relationships tend to accelerate them inwardly while they are being accelerated circumferentially. The electrons os-

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cillate about an inwardly spiraling theoretical path until they reach the equilibrium orbit determined by the field strength relationships in a radial plane, and then they travel around and around the tube with the equilibrium orbit 10a as their theoretical orbit and with constantly decreasing deviations therefrom, the velocity of the electrons, and thus their kinetic energy, being constantly increased by the continually increasing magnetic field to which they are subjected. After the electrons have traveled around in the equilibrium orbit for as many revolutions as may be desired to secure the desired energy, they are finally caused to follow a spiraling instantaneous path, as an outwardly spiraling path, to cause them to impinge upon a target of suitable material (which target may be mounted, for example, on the injector structure 11), this impingement effecting generation of X-rays, as is more fully described in certain of the above-mentioned patents and publications, or in the copending Kerst and Serber application, Serial No. 534,060, which issued as Patent No. 2,447,255 on August 17, 1948.

It has heretofore been considered necessary to have the above instantaneous value of the average field strength within the orbit double the instantaneous field strength at the orbit to maintain the proper conditions of equilibrium tending to hold the electron in a circular path if its lineal velocity is continually accelerated, and this has imposed certain undesirable design limitations upon betatrons heretofore built. I have found, however, that the desired equilibrium conditions for keeping the electron travelling in a circular orbit are achieved by maintaining appropriate relationships between the rate of change of the field strength at the orbit and the rate of change (speaking as an average across the area) within the orbit. That is, the desired equilibrium conditions are attained by having the rate of change of average field strength within the orbit double that at the orbit; and that if this condition is satisfied the absolute instantaneous values of field strength at the orbit and within the orbit do not have to bear any particular relationship to each other. I find that equilibrium conditions can be satisfactorily attained with much higher flux densities at the orbit by initially biasing the field at and about the center of the orbit negatively, so to speak. That is, by direct current means the area within the orbit can be given a certain field strength of a certain polarity when the field strength at the orbit, due to the energizing effect of the alternating current, is at or near zero; and then, as the field strength at the orbit continually rises during the period of acceleration of the electrons, the field strength within the orbit can be caused first to decrease to approximately zero and then increase with a polarity opposite to its initial polarity but the same as that at the orbit, so long as the rate of change within the orbit (speaking as an average) is double the rate of change of field strength at the orbit.

Heretofore betatrons have been built with what is in effect a single energizing coil, although for purposes of symmetry this has been arranged in two halves on the two confronting pole pieces. Magnetic conditions throughout the entire magnetic structure, however, were a function of the energizing of the single coil. For mechanical reasons it has heretofore been necessary to have spacings in the neighborhood of two inches between pole faces at the orbit, speaking of a representative 20-million electron-volt machine having a fifteen inch equilibrium orbit diameter, for example. Such spacing is a mechanical necessity in order that a suitable tube or torus may be interposed between the pole faces. Heretofore, however, since magnetic relationships had to be a function of design of the magnetic structure because of energization by a single coil, a two inch gap at the orbit was always associated with approximately a one inch gap in the central magnetic structure in the center of the torus; that is, within the orbit. For reasons associated with vertical stability of the electron in its travel this central air gap was usually divided into several gaps by the use of disks of iron between the pole pieces; but, effectively speaking, the magnetic structure in the center had an air gap in the neighborhood of one inch when the pole faces had a gap of two inches at the orbit. Such an air gap requires a substantial magneto motive force to secure suitable flux densities thereacross. For example, to secure 10,000 gauss across an air gap of one inch requires approximately 25,000 ampere-turns. I have found that I can minimize or eliminate this central air gap; and in so doing I correspondingly substan-

tially reduce the volt-amperes necessary to the energization of the betatron. Reduction of the air gap in the center of the magnetic structure, of course, would be disastrous to proper operation of the betatron with orbit diameter of the desired size; but I obviate this difficulty by associating a second coil with the central portion of the magnetic structure and energizing it in such way as to oppose the magneto motive force developed in the center of the magnetic structure by the main energizing coil, so as to be able to bring this central air gap down to a very small fraction of an inch, or even eliminate it entirely if desired, without there being a higher flux density in the center of the magnetic structure, at any instant, than is appropriate in relationship to the conditions at the orbit.

Substantial reductions in the air gap in the magnetic circuit result in deviations in the flux densities in the iron from those which occur under similar energizing conditions with a relatively large air gap. With an air gap in the neighborhood of one inch in the magnetic circuit practically all the reluctance is concentrated in the air gap and changes in reluctance in the iron relative to the flux densities set up therein are relatively unimportant. However, reduction of the central air gap to a small fraction of an inch, as .1 or .01 inch, results in the nonlinearity of iron reluctance in relation to energizing force, particularly if conditions up near saturation are approached, tending to vary the desired relationships between the field at the orbit and the field within the orbit. I have obviated this disadvantage, however, by employing means associated with the central coil for "forcing" the desired field relationships; or, more accurately speaking, the desired relationships between instantaneous change of field strength at and within the orbit. One satisfactory way to do this is to provide a third coil, in parallel with the central coil, energized as a function of the main alternating current energization of the betatron, any tendency for field deviation within the central coil causing circulating currents between the central and third coils minimizing such deviations. In fact, with a suitable arrangement of this type, relationships appropriate to equilibrium can be maintained even more stably than in connection with the present conventional betatrons now used, where the orbit diameter tends to shrink, particularly near the end of the acceleration period, because of eddy currents set up in the central portion of the magnetic structure, and saturation therein, effecting deviations from the desired relationships.

Referring now more particularly to Figures 1, 2 and 3, the main energizing coil comprising the two parts 17 and 18 on the upper and lower pole pieces corresponds to the coil heretofore comprising the sole coil on conventional betatrons. For design reasons, although tens of thousands of ampere-turns are desirable for energization of the type found in a 20-million electron-volt machine, for example, the main energizing coils have seldom exceeded a total of a hundred turns; and I prefer to use a very much lower number of turns on a high energy betatron, as for example a six-turn main energizing coil comprising three turns in the section 17 and three turns in the section 18. The wire used would preferably be a multistrand cable. This main coil is wound around the outer periphery of the circular pole piece, outside of the equilibrium orbit which would lie within the torus or tube 10, generally slightly to the outside of the center thereof.

As may be best seen in Figure 3, an induction accelerator built in accordance with the inventions I am here disclosing also has other coils mounted on its magnetic structure, and more particularly on the pole pieces thereof. The inner sections or portions of the magnetic structure lying within the tube 10 (that is, the center portions of the pole pieces 12 and 13), approach each other very closely. For example, I prefer to have these inner portions come very close together, as illustrated, with only a very small air gap or non-magnetic insulating section therebetween which is only a very small fraction of an inch, preferably of the order of .1 to .01 of an inch. For mechanical convenience in making the pole pieces, and other design considerations, it is preferable not to have a unitary solid central iron section. On this inner section or portion of the magnetic structure, within the torus 10 having the orbit therein, is a second coil comprising the sections 19 and 20 symmetrically arranged, which sections may, for example, be of three turns each and wound oppositely to the direction of winding of

the main energizing coil sections 17 and 18. On the outer diameter or outer surface of the pole pieces 12 and 13 are wound the sections 21 and 22 of a forcing coil, which sections may be of two turns each in this specific embodiment being described, for example. Also wound on the outer surface of the pole pieces 12 and 13 is a direct current biasing coil comprising the sections 23 and 24, which may, for example, be of three turns each. The flux forcing coil comprising the sections 21 and 22 must be associated with a different magnetic flux than that which cuts the back wound inner coil comprising the sections 19 and 20; and these forcing coil sections 21 and 22 are preferably outside of the orbit and approximately in the same vertical plane as the main energizing coil comprising the sections 17 and 18, as illustrated here. The location of the direct current bias coil here shown as comprising the sections 23 and 24 is not particularly critical, but maximum efficiency is attainable by placing it on the outer surface of the pole pieces as illustrated in Figure 3.

Referring now more particularly to Figure 4, it will be seen that the sections 17 and 18 of the main energizing coil are connected in parallel with a condenser 25 (in practice a bank of condensers rather than a single condenser as is schematically illustrated here). to provide a resonant or "tank" circuit; and this main circuit is energized from an alternating current source, as an alternating current generator, through the leads here identified as 26 and 27. The frequency should be relatively low, but is preferably several times that of conventional commercial current, a frequency of 180 cycles per second having proved satisfactory in various installations. Heretofore the adjacent terminals of the main energizing coil sections have been connected together; but, as may be readily seen from Figure 4, I connect these sections together through a circuit having the back wound coil sections 19 and 20 therein and also the forcing coil sections 21 and 22 (these being wound in the same direction as the main energizing coil sections) and the direct current bias coil sections 23 and 24, which may be wound in either direction in so far as alternating current conditions are concerned, but must have their direction of winding related to the polarity of direct current energization in such manner as to make the initial direct current field in the central portion of the magnetic structure of a polarity opposite to that which will eventually be created therein by the alternating current coils during the quarter cycle comprising the accelerating period.

In the absence of the flux forcing and direct current bias coil sections, and if no air gap at all were left in the center portion of the magnetic structure, the number of turns in the back wound coil comprising the sections 19 and 20 should be only about  $\frac{1}{50}$  less than in the main energizing coil associated with a structure having a one inch air gap in the center, for example. Since this condition could not be met with an integral number of turns on the coils unless the main energizing coil had 50 turns thereon, or some multiple of that number, I prefer to have the same number of turns on the back wound central coil as on the main energizing coil, whether this be 100 turns or six turns or some other number; and then to secure the desired amount of field strength in the central portion of the magnetic structure within the orbit by use of the flux forcing coil. In the absence of the forcing coil, the use of the same number of turns on the main energizing coil and the central back wound coil would theoretically result in no flux passing through the central portion of the magnetic structure; but by using a flux forcing coil in parallel with the back wound coil and subject to different flux conditions (as by being linked by the same flux that links the main energizing coil), voltage and flux conditions associated with the back wound central coil can be forced away from those which would otherwise occur and into a desired relationship. Moreover, in addition to enabling an equal number of turns to be used so as to enable the use of a central back wound coil where the main energizing coil only has a relatively few turns, the flux forcing coil acts to compensate automatically for non-linearity in the flux versus magnetomotive force characteristic curve of the iron. While these two coils (the back wound central coil and the forcing coil) form part of the main energizing circuit, variations in the reluctance of the iron in the central portion of the magnetic struc-

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ture, and tendency of the voltages across these two coils to thereby become dissimilar, causes circulating currents to flow in a circuit comprising only the central back wound coil and the forcing coil which tend to neutralize such variations in reluctance and to maintain the average flux change in the central portion of the magnetic structure in a desired relation to that at the orbit, as double.

While the direct current bias coil comprising the sections 23 and 24 is present for the primary purpose of setting up an initial field condition in the pole pieces which may be termed "negative" in character, this coil is in Figure 4 illustrated as being in parallel with the back wound and forcing coils primarily concerned with the alternating current operation of the betatron. As should be fully understood by now these coils are all spoken of as single coils because they operate electrically as single coils, even though mechanically they comprise two sections on opposite pole pieces for purposes of symmetry. This arrangement is satisfactory if the direct current energizing source, here indicated schematically as a battery 28, is capable of handling alternating currents, or of having such currents pass through, without difficulty. In practice, of course, the direct current source would normally comprise a direct current generator of relatively high amperage and low voltage characteristics; and this generator may be isolated from the alternating current, if desired, by use of a choke as shown in some of the alternative circuit diagrams to be hereafter described. The sections 21 and 22 of the flux forcing coil shield the sections 23 and 24 from having to handle flux forcing current; and the direct current bias is primarily a result of the larger number of turns in the sections 19 and 20.

The operation of the betatron, primarily from a standpoint of flux distribution, is illustrated in Figures 5-10, inclusive. Referring now more particularly to Figure 6, the curve identified as 30 indicates the field strength at the orbit, and the curve identified as 31 indicates the field strength in the central portion of the magnetic structure within the orbit. Initially, at the beginning of the period of acceleration, the field strength at the orbit would be slightly below zero or at zero, as indicated by the "x" at the intersection of the zero axis and the curve 30, this point being identified as 30a, as this provides conditions suitable for injection of the electrons. At the same instant of time, by virtue of the direct current bias, the field strength through the central portion of the magnetic structure would be at some appropriate negative value, as 10,000 gauss, as indicated by the "x" at the point of origin of the curve 31, this point being identified as 31a. This is illustrated in another and perhaps more readily understandable way in Figure 5, where only a single flux line is indicated as crossing the orbit, to show approximately zero field conditions or slightly negative field conditions at the orbit; but a large number of flux lines are shown as passing through the central portion of the magnetic structure, with a polarity in a given direction, by arrows pointing upwardly in the center.

When the electrons have been injected, this generally being for a period of only a few microseconds, the effect of the rising alternating current energization, which is rising on the positive side of a cycle, is a start to cause flux of an opposite polarity to begin to cross the orbit, and to decrease the field strength of the magnetic conditions in the central portion of the magnetic structure, this continuing until the alternating current has reached half its positive maximum, at which point the flux lines through the central portion of the magnetic structure are theoretically zero. This next condition is illustrated in Figures 7 and 8. In Figure 8 the "x" on the curve 30 indicates that the field through the orbit has reached approximately half its maximum, this point being identified as 30b, corresponding to the half maximum of the energizing alternating current; and the field strength through the central portion of the magnetic structure has decreased to zero at this instant of time, as indicated by the "x" at the intersection of the curve 31, this point being indicated as 31b, with the zero axis. This same condition is shown in the form of a flux pattern diagram in Figure 7, where it will be seen that there are an appreciable number of flux lines through the tube at and about the orbit, with a polarity opposite to those which previously existed in the central portion of the magnetic structure; and that there are no lines of force in such central portion.

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Eventual conditions at the conclusion of the period of acceleration of the electrons are illustrated in Figures 9 and 10. In Figure 10 it will be seen that the field strength through the orbit and the field strength through the central portion of the magnetic structure have both reached the same value with the same polarity at the same instant, as indicated by the single "x" marking the point here identified as 30c. This same condition is illustrated in flux plot diagram form in Figure 9, where it will be seen that a substantial number of lines of force cross at and near the orbit, and the polarity of the field in the central portion of the magnetic structure is in the same direction as that at the orbit and of the same value per unit of area. By initially biasing the field in the central portion so that it is of the same field strength but of opposite polarity as that which it reaches at the peak of the positive cycle of the energizing alternating current, I am able to have the change of field strength in the central portion twice that at the orbit, and yet have the flux densities in the pole face at the orbit and in the central portion of the magnetic structure the same at the conclusion of the accelerating period. That is, if the iron will satisfactorily handle 12,000 gauss or lines per square centimeter, I can have the central portion of the magnetic structure go through conditions from 12,000 gauss "negative" to 12,000 gauss "positive" while the field strength at the orbit is going from zero to 12,000 gauss. This satisfies the relationships necessary to maintain an equilibrium orbit in the tube; and yet enables a given pole face area at the orbit to be worked up to double the flux densities heretofore possible, since heretofore, where both the central portion and the orbit started at zero, usable flux densities were limited by saturation being reached at the central portion of the magnetic structure. In the decreasing half of the positive portion of the cycle and throughout the entire negative portion of the alternating current cycle, the equipment would be inoperative and injection would not be effected until conditions had again reached the stage illustrated in Figures 5 and 6. During this period which is inoperative in so far as electron acceleration is concerned, the flux densities at the orbit would go through the curve indicated by the continuation of the curve 30; but the field conditions in the central portion of the core, indicated by the curve 31, would substantially level off upon saturation of the iron and then extend straight across, as illustrated by the horizontal portion of the curve 31.

In any event, the field strength at the orbit can, by use of my improved apparatus and method, be made approximately double that heretofore possible for a given size magnet and tube. In addition, since the central coil is back wound with respect to the main energizing coil, the current quantities (which determine the power consumption) are greatly reduced under what would be expected from a consideration of only the voltage drop across the alternating current line terminals, resulting in still further reduction of volt amperes, and enabling the condensers to be of smaller capacity. In this regard, it will be understood, of course, that the resonant period of the system is determined by the total effective inductance in parallel with the condenser 25; that is, the inductance comprises the series parallel circuit including not only the main energizing coil but also the center coil, the forcing coil and the direct current bias coil (where no choke is used). However, in so far as the alternating current terminals are concerned, the energizing circuit acts as though the condenser 25 had in parallel with it a single coil of an inductance equal to such effective inductance.

Referring now more particularly to Figure 11, an alternative circuit will be briefly described. In order to avoid repetition of the purposes and functions of parts shown on this circuit diagram reference numerals 100 higher than those heretofore used will be used in connection with analogous parts. The main energizing coil is here shown as comprising the sections 117 and 118, the outer terminals of these sections being connected to a condenser 125 having the alternating energizing current developed thereacross by leads 126 and 127. Connection between the two sections of the main energizing coil are completed through a series parallel arrangement comprising the sections 119 and 120 of the back wound central coil and the sections 121 and 122 of the forcing coil. The circuit shown here differs from that shown in Fig-

ure 4 primarily in that no separate direct current bias coil is used, a direct current circuit being set up through the back wound central coil and the forcing coil by a source of direct current here indicated diagrammatically as the battery 128. The forcing coil has a lesser number of turns than the back wound coil, and accordingly there is a certain effective ampere-turn direct current energization in a direction biasing the field through the central portion of the magnetic structure "negatively"; that is, with a polarity opposite to that created by the main energizing coil during the rising portion of the positive pulse, as has been explained heretofore. This is a perfectly operable system, its principal requirement being an exceedingly high current and low voltage direct current source, as for example a homopolar generator.

Figure 12 shows another embodiment of my inventions, and in this case reference numerals 200 higher than those used in connection with Figures 1-10 will be applied to analogous parts. Here the main energizing coil comprising the sections 217 and 218 again has its outer terminals connected to a condenser 225 having the alternating energizing current developed thereacross by leads 226 and 227. The inner terminals of the two sections 217 and 218 are again connected together through a series parallel circuit comprising the sections 219 and 220 of the back wound central coil and the sections 221 and 222 of the forcing coil, this coil again having fewer turns than the back wound coil, which is preferably of the same number of turns as the main energizing coil. In the form of my invention shown in this circuit diagram the initial field bias in the central portion of the magnetic structure in a negative direction is achieved by the total action of both the back wound coil and the forcing coil when these are energized from a direct current source indicated diagrammatically as the battery 228. A difference between this arrangement and that shown in Figure 11 is that in the circuit diagram of Figure 12 I employ a choke 235 to keep alternating current, whether it be the main energizing current or circulating currents connected with the forcing action, out of the direct current source 228. As will be noted, the arrangement is such that a separate connecting lead 236 is provided between the outer terminals of the sections 221 and 222 of the forcing coil, rather than having this connection completed through the direct current source. Both the flux forcing coil and the back wound coil act as direct current bias coils, effecting mainly the central flux.

Figure 13 shows an arrangement wherein the direct current bias means is completely independent of the alternating current portions of the circuit. In describing the circuit of Figure 13 reference numerals 300 higher than those used in the first description will be applied to analogous parts. The main energizing coil comprising the sections 317 and 318 has its outer terminals connected to the condenser 325, with the AC energizing current again being developed across this condenser through the leads 326 and 327. The inner terminals of the two sections 317 and 318 of the main coil are connected together through the series parallel circuit comprising the sections 319 and 320 of the back wound central coil and 321 and 322 of the forcing coil, the inner terminals of all these last-mentioned sections being connected to the inner terminals of the main coil sections and the outer terminals of the central and forcing sections being connected together by the leads 336 and 337.

A direct current bias coil comprising the sections 323 and 324 is in circuit only with the direct current source 328 and the choke 329. This provides an independent direct current bias circuit which does not have to be considered in calculation of the alternating current circuit; and alternating currents which might otherwise be set up in this direct current circuit by coupling with the alternating current coils are blocked by the choke 329.

Figure 14 shows an embodiment of my invention which provides readily adjustable means for varying the forcing action of the forcing coil. This not only facilitates design of induction accelerator apparatus, in that it enables a very wide adjustment of the forcing action, but also enables variation of the diameter of the equilibrium orbit in a convenient manner at any time. In betatrons embodying my inventions as heretofore described, the movement of turns of the forcing coil and its location must be approximately determined, and the final adjustments can be made by some movement of the forcing coil up and down in the leakage flux area of the main energizing coil,

adjustment in this manner normally not permitting more than about 10% variation. By the arrangement shown in Figure 14, however, I provide a forcing arrangement which still operates as a function of the main energizing current of the system, and yet is readily adjustable or variable over a relatively wide range.

In the circuit diagram of Figure 14 and using reference numerals 400 higher than those initially used in this specification, it will be seen that the sections 417 and 418 of the main energizing coil again have their outer terminals connected to the condenser 425 which has the alternating energizing current developed thereacross through the leads 426 and 427. The inner terminals of the sections 417 and 418 are connected together through a series parallel circuit which comprises the sections 419 and 420 of the back wound central coil on the one hand (connected together by the lead 437) and the secondary 440a of a transformer 440 having a primary 440b. The secondary 440a, as illustrated, is of the tapped type permitting ready adjustment of the number of turns thereon; and the transformer as a whole would generally have a maximum ratio of 1:1, adjustment of the tap connection to the secondary enabling the number of turns there to be cut down to cause the transformer to act as a step down transformer of substantially any suitable ratio. It will be understood, of course, that neither of the coils of the transformer 440 would be wound on the pole pieces or magnetic structure of the betatron in this form of my invention. The transformer 440 provides, in its secondary, a source of energy which is a true function of the main energizing alternating current across the outer terminals of the main coil sections; and, by having this secondary in parallel with the sections 419 and 420 of the back wound central coil, the amount of forcing action can be readily controlled by adjustment of the tap connection to the secondary 440a. Cutting down the number of turns in the operable portion of the secondary 440a tends to reduce the forcing action and increase the diameter of the equilibrium orbit; while increasing the number of turns in circuit in the secondary decreases the diameter of the equilibrium orbit. At any particular desired setting, of course, the forcing action, the circulation of currents between this transformer secondary and the sections 419 and 420 when desired field strength relationships tend to diverge, stabilizes the position of the orbit and prevents undesired change therein during the acceleration period for the electrons. While this circuit has not been complicated by a showing of direct current bias coils and means, it will be understood that I prefer to employ with an arrangement of this kind a direct current biasing system of the kind shown in any of the preceding figures.

While I have shown and described certain embodiments of my invention, it is to be understood that it is capable of many modifications. Changes, therefore, in the construction and arrangement may be made without departing from the spirit and scope of the inventions as disclosed in the appended claims.

I claim:

1. A method of operating a magnetic induction accelerator for accelerating charged particles in a generally circular orbit, comprising initiating a period of acceleration with a field strength in the neighborhood of zero at the orbit and a relatively strong field of a certain predetermined polarity near the center of the orbit and then increasing the field strength at the orbit and simultaneously varying the field strength near the center to maintain a constant predetermined ratio of rate of change between the two fields.

2. A method of operating a magnetic induction accelerator for accelerating charged particles in a generally circular orbit, comprising initiating a period of acceleration with a field strength in the neighborhood of zero at the orbit and a relatively strong field of a certain polarity near the center of the orbit and then increasing the field strength at the orbit and, during the same period, decreasing the field strength near the center to zero and then increasing it with the opposite polarity.

3. A method of operating a magnetic induction accelerator for accelerating charged particles in a generally circular orbit, comprising initiating a period of acceleration with a field strength in the neighborhood of zero at the orbit and a relatively strong field of a certain polarity near the center of the orbit and then increasing the field strength at the orbit and, during the same period, decreasing

ing the field strength near the center to zero and then increasing it with the opposite polarity with a rate of change double that of the change of field strength at the orbit at any instant.

4. A magnetic induction accelerator for charged particles comprising: a closed vessel defining an annular chamber within which such particles may move in a generally circular orbit; a magnetic structure having a portion within such orbit; a main accelerating field-producing coil on said magnetic structure, said coil having a capacitance associated therewith; a second field-producing coil on said magnetic structure, said second coil having a diameter less than that of said orbit, this second coil being in series with said main accelerating coil and oppositely wound with respect thereto; projecting apparatus for projecting charged particles within said chamber with a substantial initial velocity; and energizing apparatus connected to said coils for producing a magnetic field varying as a function of time.

5. A magnetic induction accelerator for charged particles comprising: a closed vessel defining an annular chamber within which such particles may move in a generally circular orbit; a magnetic circuit comprising at least one pair of opposed, generally circular pole pieces which are substantially coaxial with said orbit, said circuit having a portion with a suitable air gap at the orbit and a portion within such orbit with not more than a relatively very small gap therein; a main accelerating field-producing coil associated with said magnetic circuit, said coil having a diameter greater than said orbit and having a capacitance associated therewith; a second field-producing coil associated with said magnetic circuit, said second coil being in series with the main coil and having a diameter less than that of said orbit; projecting apparatus for projecting charged particles within said chamber with a substantial initial velocity; and energizing apparatus connected to said coils for producing a magnetic field varying as a function of time, the connections being of such a character that the magnetic effect of said second coil on the portion of the magnetic circuit within the orbit is opposite to that of the main coil.

6. A magnetic induction accelerator for charged particles comprising: a closed vessel defining an annular chamber within which such particles may move in a generally circular orbit; a magnetic structure having a portion within such orbit; a main accelerating field-producing coil on said magnetic structure; a capacitance connected to said coil; a second field-producing coil on said magnetic structure having a diameter less than that of said orbit; projecting apparatus for projecting charged particles within said chamber with a substantial initial velocity; energizing apparatus connected to said coils for producing a magnetic field varying as a function of time, the connections being of such a character that the magnetic effect of said second coil on the portion of the magnetic structure within the orbit is opposite to that of the main coil and approximately equal thereto; and a third coil for forcing a desired amount of flux through the portion of the magnetic structure within the orbit.

7. A magnetic induction accelerator for charged particles comprising: a closed vessel defining an annular chamber within which such particles may move in a generally circular orbit; a magnetic structure comprising opposed, generally circular pole pieces which are substantially coaxial with said orbit, said pole pieces having a suitable air gap therebetween at the orbit and a portion within such orbit with not more than a relatively very small gap therein; a main field-producing coil on said magnetic structure having a diameter greater than that of said orbit; a capacitance connected to said coil; a second field-producing coil on said magnetic structure having a diameter less than that of said orbit; projecting apparatus for projecting charged particles within said chamber with a substantial initial velocity; energizing apparatus connected to said coils for producing a magnetic field varying as a function of time, the connections being of such a character that the magnetic effect of said second coil on the portion of the magnetic structure within the orbit is opposite to that of the main coil and approximately equal thereto; and a third coil for forcing a desired amount of flux through the portion of the magnetic structure within the orbit.

8. A magnetic induction accelerator for charged particles comprising: a closed vessel defining an annular chamber within which such particles may move in a gen-

erally circular orbit; a magnetic structure comprising opposed, generally circular pole pieces which are substantially coaxial with said orbit, said pole pieces having a suitable air gap therebetween at the orbit and a portion within such orbit with not more than a relatively very small gap therein; a main accelerating field-producing coil on said magnetic structure; a capacitance connected to said coil; a second field-producing coil on said magnetic structure having a diameter less than that of said orbit; projecting apparatus for projecting charged particles within said chamber with a substantial initial velocity; energizing apparatus connected to said coils for producing a magnetic field varying as a function of time, the connections being of such a character that the magnetic effect of said second coil on the portion of the magnetic structure within the orbit is opposite to that of the main coil and approximately equal thereto; and a third coil for forcing a desired amount of flux through the portion of the magnetic structure within the orbit, this third coil having a diameter greater than that of said orbit and being connected in parallel with said second coil.

9. A magnetic induction accelerator for charged particles comprising: a closed vessel defining an annular chamber within which such particles may move in a generally circular orbit; a magnetic structure having a portion within such orbit; a main accelerating field-producing coil on said magnetic structure; a capacitance associated with said coil; a second field-producing coil on said magnetic structure having a diameter less than that of said orbit, this second coil being in series with the first coil and oppositely wound with respect thereto, the coils having an equal number of turns; projecting apparatus for projecting charged particles within said chamber with a substantial initial velocity; energizing apparatus connected to said coils for producing a magnetic field varying as a function of time; and a third coil for forcing a desired amount of flux through the portion of the magnetic structure within the orbit, this third coil having a diameter greater than that of said orbit and being connected in parallel with said second coil.

10. A magnetic induction accelerator for charged particles comprising: a closed vessel defining an annular chamber within which such particles may move in a generally circular orbit; a magnetic circuit comprising at least one pair of opposed, generally circular pole pieces which are substantially coaxial with said orbit, said circuit having a suitable air gap at the orbit and a portion within such orbit with not more than a relatively very small gap therein; a main accelerating field-producing coil operatively associated with said magnetic circuit, said coil having a diameter greater than that of said orbit and having a capacitance connected thereto; a second field-producing coil operatively associated with said magnetic circuit, said second coil having a diameter less than that of said orbit, this second coil being in series with the first coil and oppositely wound with respect thereto, the coils having an equal number of turns and both coils being of relatively few turns; projecting apparatus for projecting charged particles within said chamber with a substantial initial velocity; energizing apparatus connected to said coils for producing a magnetic field varying as a function of time; and a third coil for forcing a desired amount of flux through the portion of the magnetic circuit within the orbit, this third coil having a diameter greater than that of said orbit and connected in parallel with said second coil.

11. A magnetic induction accelerator for charged particles comprising: a closed vessel defining an annular chamber within which such particles may move in a generally circular orbit; a magnetic structure having a portion within such orbit; a main field-producing coil on said magnetic structure; a capacitance connected to said coil; projecting apparatus for projecting charged particles within said chamber with a substantial initial velocity; energizing apparatus connected to said main coil for producing a magnetic field varying as a function of time; and a second coil for causing the portion of the magnetic structure within the orbit to have an initial polarity equal to and opposite from the maximum polarity developed as the orbit by the energizing apparatus and main field-producing coil.

12. A magnetic induction accelerator for charged particles comprising: a closed vessel defining an annular chamber within which such particles may move in a gen-

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erally circular orbit; a magnetic circuit having a portion within such orbit; a main field-producing coil associated with said magnetic circuit; a capacitance associated with said coil; projecting apparatus for projecting charged particles within said chamber with a substantial initial velocity; energizing apparatus connected to said main coil for producing a magnetic field varying as a function of time; a second coil associated with the portion of the magnetic circuit within the orbit and having a diameter less than that of the orbit; and a direct current source connected to said second coil for causing the portion of the magnetic circuit within such orbit initially to have a magnetic polarity opposite to that eventually developed by the energizing apparatus and main field-producing coil.

13. A magnetic induction accelerator comprising the combination of an evacuated annular container, a shell-type magnetic core having a closed central member coaxially surrounded by said container, means for introducing electrons into said container, means for magnetically biasing said central core member, means for subjecting said electrons to a time-varying magnetic field which is oriented to accelerate electrons in said container, means for superimposing a biasing non-varying magnetic field on said variable field, and means for discharging said electrons.

14. A magnetic induction accelerator for charged particles comprising: a closed vessel defining an annular chamber within which such particles may move in a generally circular orbit; a magnetic circuit having a portion within such orbit; a main field-producing coil associated with said magnetic circuit; projecting apparatus for projecting charged particles within said chamber with a substantial initial velocity; energizing apparatus connected to said main coil for producing a magnetic field varying as a function of time; a second coil associated with the por-

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tion of the magnetic circuit within the orbit and having a diameter less than that of the orbit; and a direct current source connected to said second coil for causing the portion of the magnetic circuit within such orbit initially to have a magnetic polarity opposite to that eventually developed by the energizing apparatus and main field-producing coil.

15. A magnetic induction accelerator for charged particles comprising: a closed vessel defining an annular chamber within which such particles may move in a generally circular orbit; a magnetic field structure associated with said vessel and which includes a central induction pole portion within the orbit and confronting control pole portions at said orbit having an air gap therebetween, the reluctance of the magnetic path through said induction pole portion being practically negligible when compared with that through said control poles across the said air gap; a main field producing coil on said magnetic structure surrounding said control pole portions; an auxiliary field producing coil on said magnetic structure surrounding only said central induction pole portion within said orbit; and energizing apparatus connected to said coils for producing a magnetic field varying as a function of time, the said coil connections being of such character that the magnetic effect of said auxiliary coil on said induction pole portion of said magnetic structure is opposite to that of said main coil.

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