Nov. 24, 1953 W. F. WESTENDORP 2,660,673

MAGNETIC INDUCTION ACCELERATOR

Filed Sept. 15, 1945 2 Sheets-Sheet 1

Fig. 1.

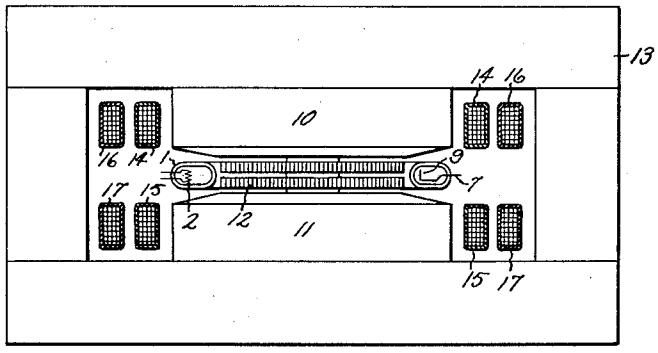


Fig. 3.

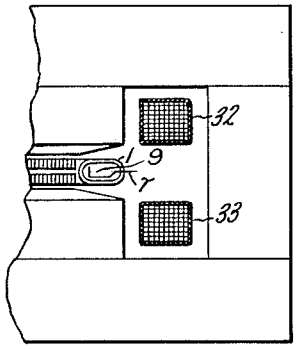


Fig. 2.

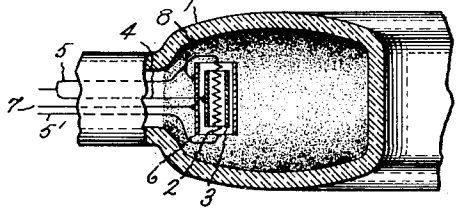


Fig. 4.

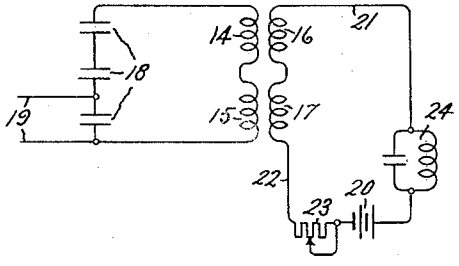


Fig. 5.

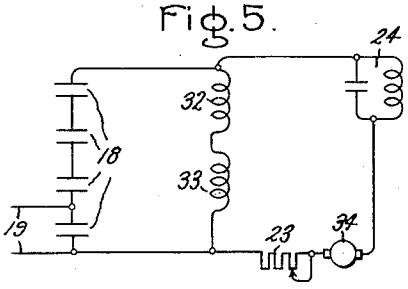
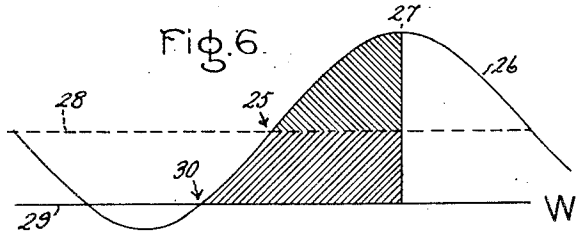


Fig. 6.



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Fig. 7.

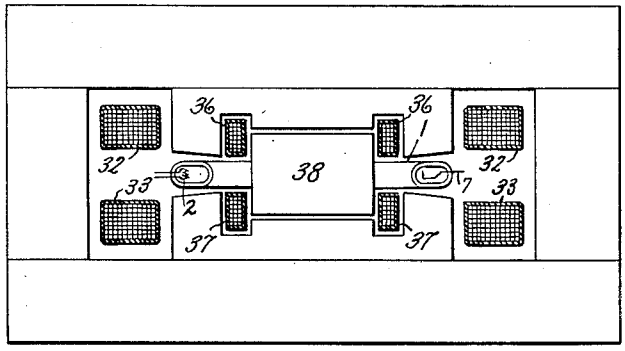


Fig. 8.

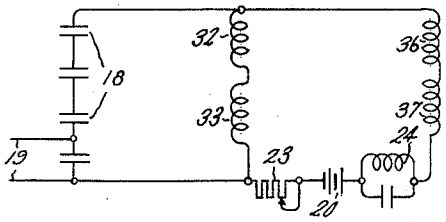


Fig. 9.

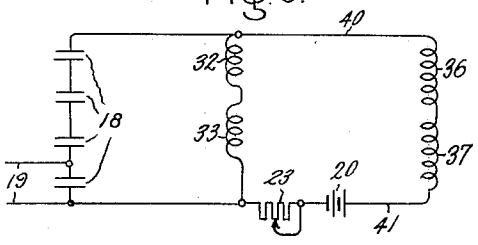


Fig. 11.

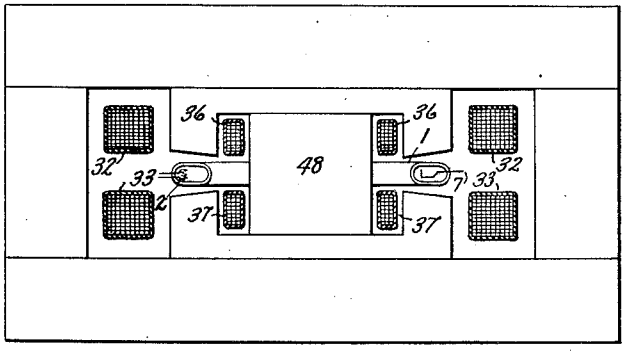


Fig. 10.

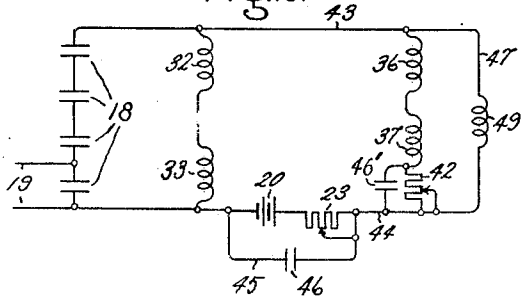
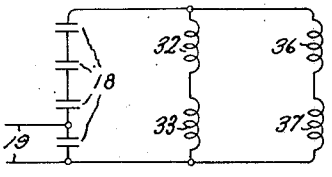


Fig. 12.



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UNITED STATES PATENT OFFICE

2,660,673

MAGNETIC INDUCTION ACCELERATOR

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Application September 15, 1945, Serial No. 616,634

1 Claim. (Cl. 250—27)

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The present invention relates to apparatus for accelerating charged particles, and in particular electrons, by means of magnetic induction. My invention is especially applicable to electron accelerator apparatus of the type disclosed in U. S. Kerst Patent 2,297,305, patented September 29, 1942.

Such apparatus typically includes a hermetically-sealed container and electromagnetic means for producing therein a time-varying magnetic field of such space distribution as to cause charged particles introduced into said container at timed intervals to be progressively accelerated. When the charged particles have been accelerated to a desired energy, they may be caused to produce desired effects; for example, electrons may be caused to produce X-rays by striking a target.

It is the object of my present invention to increase the efficiency of such accelerating apparatus and also to provide means for so improving their mode of operation that a given accelerating effect can be produced with apparatus of decreased size and cost.

In accordance with my present invention these and other beneficial results in the operation of electromagnetic accelerators are obtained by supplementing the time-varying magnetic field whereby charged particles are caused to travel at continuously accelerated velocity with a biasing field.

In accordance with one modification of my present invention, a time-varying magnetic field for producing such acceleration is generated by the conjoint effect of unidirectional and alternating magnetic fields. In accordance with another modification a biasing alternating current is used. These and other novel features of the present invention will be pointed out with greater particularity in the accompanying claim.

My invention is illustrated by the accompanying drawings in which Fig. 1 is a partially sectionalized front elevational view of an accelerating apparatus embodying my invention; Fig. 2 is a sectional view of the cathode end of the accelerating chamber; Fig. 3 is a front elevation of one end of a modification; Figs. 4, 5, 8 to 10 and 12 are diagrams illustrating electrical circuits for generating unidirectional and alternating magnetic fields; Fig. 6 is a diagrammatic representation of field excitation; and Figs. 7 and 11 are vertical sections of modified magnetic structures wherein unidirectional and alternating fields are combined.

Figs. 1 and 2 illustrate an electron accelerator

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comprising an evacuated annular container 1, which may consist of glass, into the interior of which electrons are introduced and accelerated to a high energy. The electrons are emitted by a filamentary cathode 2 which is enclosed by an electro-static shield 3, the latter being electrically connected to the filament by the conductor 4. An opening is provided for the egress of electrons. The cathode filament 2 is supported bp wires 5, 5' sealed into the wall of the container 1. An anode 6 supported by a stem wire 7 surrounds the cathode and may be connected as shown to a conductive coating 8 on the interior of the container. A target 9 is provided as indicated in Fig. 1.

Suitable means should be provided (here being omitted to simplify the drawing) for injecting the electrons at a predetermined part of the cycle of the time-varying field and for causing the accelerated electrons to strike the target. Such means is described in Kerst Patent 2,297,305 and in a Kerst U. S. Patent 2,394,070 patented February 5, 1946. Such means is described also in an article entitled "A 20-million electron-volt betatron or induction accelerator" in R. S. I. (Review of Scientific Instruments), vol. 13, pages 387–394, September 1942.

The accelerating mechanism comprises a shell-type magnetic core having pole pieces 10, 11 and a centerpiece 12 consisting of two laminated magnetic disks separated by appropriate spacers. The pole pieces 10, 11 and the part 12 are coaxially arranged with respect to the container and are connected to a magnetic frame 13. On the frame 13 are mounted a set of alternating current energizing coils 14, 15. The latter are located as indicated in the figure respectively above and below the plane of the annular container and external thereto. Additional coils 16, 17 are provided also external to the annular container and located as shown respectively above and below the annular container. The coils 16, 17, as will be explained in connection with Fig. 4, are energized with unidirectional current.

As shown in Fig. 4, the coils 14, 15 are connected in series to a source of alternating current which in this case is represented by a plurality of series-connected capacitors 18. These capacitors are supplied with alternating current by the conductors 19 which lead to a suitable A. C. (alternating current) power source (not shown). The windings 16 and 17 are energized from a direct current source which here is represented by the battery 20. The latter is connected to the coils 16, 17 by the conductors 21,

22 in series with an adjustable resistance 23 and a filter 24 whereby the alternating current is blocked from circulation in the unidirectional current circuit.

As explained in Kerst Patents 2,297,305 and 2,394,070, the electrons are caused to be accelerated in an annular path by the time-varying magnetic field, after having been injected during a brief interval approximately at the zero value of the magnetic field, as indicated at 25 by the arrow in Fig. 6. It is assumed that the magnetic field to be generated by an alternating current is represented by the full line curve 26. Acceleration of the electrons continues up to the maximum value 27 of the magnetic field, which is assumed to be in phase with the alternating energizing current. The magnetic field does not produce a useful effect during the time interval of decreasing current and during the time interval of reversed polarity of the energizing current. Hence, in the absence of a biasing magnectic field, only the portion of the energy represented by the shaded area above the dotted base line 28 or the positive quarter cycle as conventionally shown is utilized for electron acceleration. When a unidirectional flux is superimposed on the alternating flux whereby the magnetic field is generated, then one polarity of magnetic field is increased and the opposite polarity is decreased. In effect, the resulting asymmetric alternating magnetic field rises from a new zero value indicated by the solid base line 29 when the unidirectional flux is in a negative direction as conventonally shown. If the injection of the electrons is timed to occur near the zero field value, that is, at 30, the acceleration continues throughout a longer period as represented by the added shaded area. The period of reverse field is decreased as indicated.

The alternating current component in the presence of a biasing unidirectional component is decreased below conventional requirements to approximately 54 per cent. A unidirectional current equal to about 85 to 95 per cent of the new crest value of alternating current is employed in conjunction with the alternating current for generating the accelerating field. As shown in Fig. 3, a single set of coils 32, 33 may be employed. As shown in Fig. 5 unidirectional current excitation of these coils is superimposed on the alternating current excitation. The alternating current is supplied by the capacitors 18, as previously stated in connection with Fig. 4. The unidirectional current is supplied from a direct current source, here represented by a generator 34 which is connected in series with the adjustable resistor 23 and the filter 24.

In my improved apparatus, as embodied in structures shown in Figs. 1 and 3, the power losses in the electron accelerator may be reduced to values as low as 30 to 40 per cent of the losses occurring in conventional alternating current excitation of electron accelerators.

It will be observed that unidirectional magnetization is necessary only at the electron orbit. It is the field at the orbit which keeps the electrons traveling in a circle. This may be represented by the formula

$$HR\times 3\times 10^{-4}=K \text{ (total electron energy in megavolts)}$$

H is the magnetic field in oersteds, R is the radius of the orbit in centimeters.

No unidirectional flux is needed in the laminated core enclosed by the orbit. The only requirements for the flux passing through the electron orbit is that its total change from the instant of zero field intensity at the orbit fulfills the so-called 2:1 relation which can be expressed as follows:

$$\Delta\phi=2\pi R^2B$$

$\Delta\phi$ is the total change of flux through the orbit; R is the radius of the orbit; B is the flux density at the orbit. A unidirectional component is undesirable because it may cause saturation when added to the alternating flux.

In accordance with another feature of my invention as shown in Fig. 7, an undesired unidirectional flux through the central part of the core is reduced or eliminated by bucking coils 36, 37 which are of lesser diameter than the annular container and are located as illustrated in a channel or groove of the magnetic core. A large laminated core member 38 is provided between the pole pieces and threaded through the annular container 1, to avoid stray magnetic fields in the region of the annular container.

As shown in Fig. 8, the bucking coils 36, 37 are connected to receive direct current from the same source, conventionally indicated by the battery 20, as the coils 32, 33. The filter 24 blocks alternating current from flowing in the coils 36, 37.

By providing coils 36, 37 as shown in Fig. 9, which have sufficient number of turns required to oppose the alternating voltages induced in the windings 32, 33, while at the same time furnishing an excess number of ampere turns to neutralize the unidirectional component of flux, the energizing circuit shown in Fig. 9 need not be provided with a blocking filter. The circuit 40, 41 contains a direct current source, as represented by the battery 20 and an adjustable resistor 23 to regulate the value of the unidirectional current.

Fig. 10 shows a modified arrangement of circuit elements. The windings 36, 37 are connected in series with an adjustable resistor 42 to the conductors 43, 44, the latter containing a unidirectional source, as represented by a battery 20 in series with which is provided an adjustable resistor 23, the latter being shunted by a circuit 45 containing a shunt-connected capacitor 46. A bleeder circuit 47 containing a reactor 49, is connected to by-pass some of the unidirectional current component of the windings 36, 37 which have a greater number of turns than the coils 32, 33. The number of turns of the coils 36 and 37 is so chosen that their induced alternating voltages equal the voltages of the capacitor bank 18. With proper size of the gaps in the central core 38, shown in Fig. 7, a circular electron orbit will be obtained without any alternating current flowing in the coils 36 and 37. By choosing the number of turns of the coils 36, 37 sufficiently in excess of the coils 32, 33, a desired equality of voltages and the condition of zero alternating current can be attained. However, the number of turns in the coils 36, 37 then will be too large to compensate the direct current flowing in the coils 32, 33. Hence the by-pass circuit 47 is provided.

Due to the direct connection between the coils 32, 33, and 36, 37, as shown in Fig. 10, these coils have equal alternating flux linkages. The resulting fluxes of fixed ratios will fulfill the required 2:1 relation. This fixed flux ratio makes possible the elemination of the gaps in the central core which are indicated in Fig. 7.

A substantially closed core 48 can be provided

instead, as shown in Fig. 11, the electrical connections remaining as shown in Fig. 10. The closing of the core member which is threaded through the space enclosed by the envelope 1 results in the flow of alternating current in the coils 36, 37, counteracting the large number of alternating current ampere turns in the coils 32 and 33. For the passage of this alternating current through the coils 36, 37, a by-pass capacitor 46 is provided across the resistor 42. The elimination of the central gaps in the core 48 results in a reduction of the magnetic energy stored in the accelerator at the peak of the energizing current wave. This energy is stored principally in the air gaps where the product of the field intensity and the flux density is high. By the elimination of the central gaps, this stored energy can be reduced by 50% or more depending on the space taken up by the evacuated container. The final result will be a marked reduction in the size of the capacitor bank 18.

As described in Kerst Patent 2,297,305 and in Physical Review, vol. 60, pages 47 to 53, July 1, 1941, the accelerated electrons may be caused to strike a target, such as indicated at 9, Fig. 1, by taking advantage of the saturation of the central core to produce sufficient contraction of the electron orbit at the desired instant. In an electron accelerator such as described in Kerst Patent 2,297,305, the saturation of the central core always occurs uncontrollably at the same electron energy.

In an electron accelerator, the pole pieces of which are provided with grooves containing windings 36, 37 as indicated in Fig. 11, desired regulation may be provided for the unidirectional field component so that saturation of the central core by which the electron orbit is contracted may be produced at will. Saturation of the core is the result of the combined excitation of the alternating and unidirectional currents in the windings 32, 33, and 36, 37. If insufficient unidirectional component is contributed by the groove coils 36, 37, contraction of the orbit must occur. The excitation of the coils 36, 37 can be controlled by a variable resistor 42 as shown in Fig. 10.

It is true that the direct connection of groove coils 36, 37 to main coils 32, 33 does maintain equal alternating voltages across both sets of coils; but even though this means equal flux linkages, it does not mean proportionality between the flux in the center of the central core 48 and the field at the orbit because the groove coils 36, 37 have considerable leakage flux across the grooves which does not go through the center of the core 48. Therefore, the required 2:1 relation will be upset by saturation, and the orbit will contract until the electrons strike the target.

It is possible to produce saturation of the central core over a wide range of values of the main alternating and unidirectional operating currents. The ratio of alternating current to direct current is maintained throughout this range of values (for example, at 0.866). The control re-

sistor 42, Fig. 10, in circuit with coils 36, 37 is used to produce saturation at the crest of the current for each setting of the current in the coils 32, 33. A wide range of output X-ray energies can thus be obtained in a simpler manner and without the use of orbit shift circuits involving high current vacuum tubes or other control mechanism.

In Fig. 12 is shown an electric system which is adapted to be used for operating the type of electron accelerator such as shown in Fig. 11. The accelerator is operated solely by alternating current and the required 2:1 relation heretofore referred to is maintained by the direct connection of the coils 32, 33 and 36, 37 to the source of alternating current which is again represented by the capacitor bank 18. The windings 36, 37 will carry a current opposing the magnetizing effects of the main windings 32, 33 and thereby the windings 36, 37 will function to bias the excitation of the core to the proper value insuring the 2:1 relation and a circular orbit of the correct diameter.

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

A magnetic induction accelerator comprising the combination of an annular container in which electrons may be accelerated in an orbital path, means for introducing electrons therein, a magnetic core having a member coaxial with said container, a set of windings for said core concentric to and of larger diameter than said container, a source of alternating current connected across said windings to energize said windings with alternating current, a series circuit including a second set of windings for said core member of lesser diameter than said annular container, an adjustable resistor shunted by a capacitor, and a source of direct current connected across said first mentioned windings to superimpose a biasing direct current upon the alternating current in said first mentioned windings, said second set of windings having a number of turns correlated with the number of turns in said first mentioned set of windings to provide an induced alternating voltage essentially equal to and opposing the alternating voltage of said source of alternating voltage, and a bleeder circuit comprising a reactor connected across said second set of windings to by-pass some of the unidirectional component of said second set of windings.

WILLEM F. WESTENDORP.

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