Oct. 27, 1942. A. BOUWERS ET AL 2,299,792

ELECTRIC DISCHARGE TUBE

Filed May 26, 1939 2 Sheets-Sheet 1

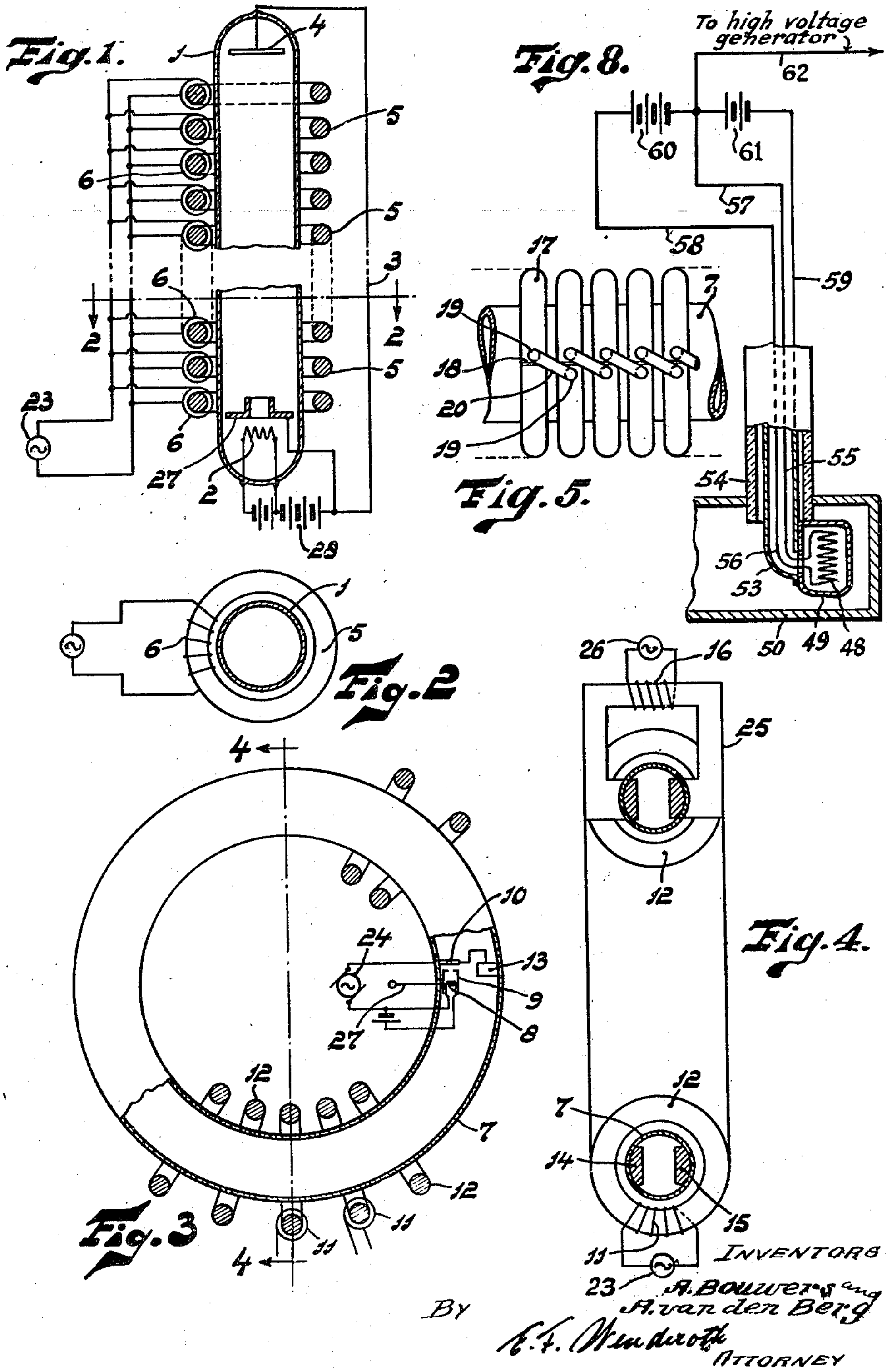

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Fig. 6

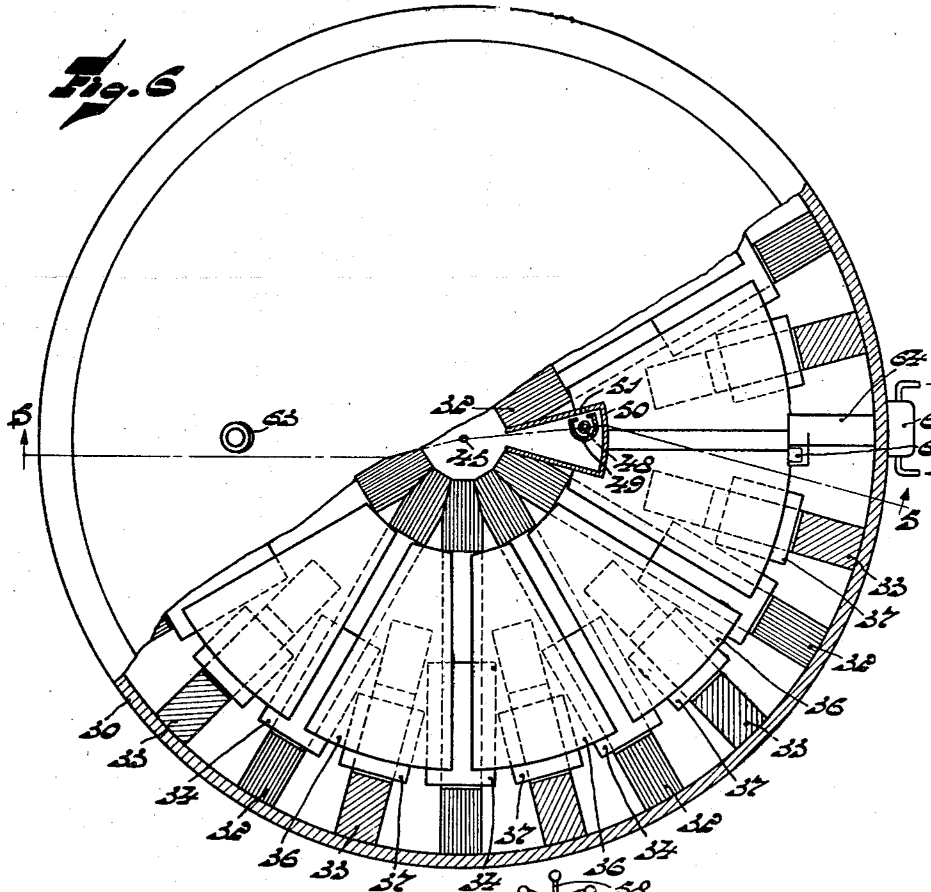
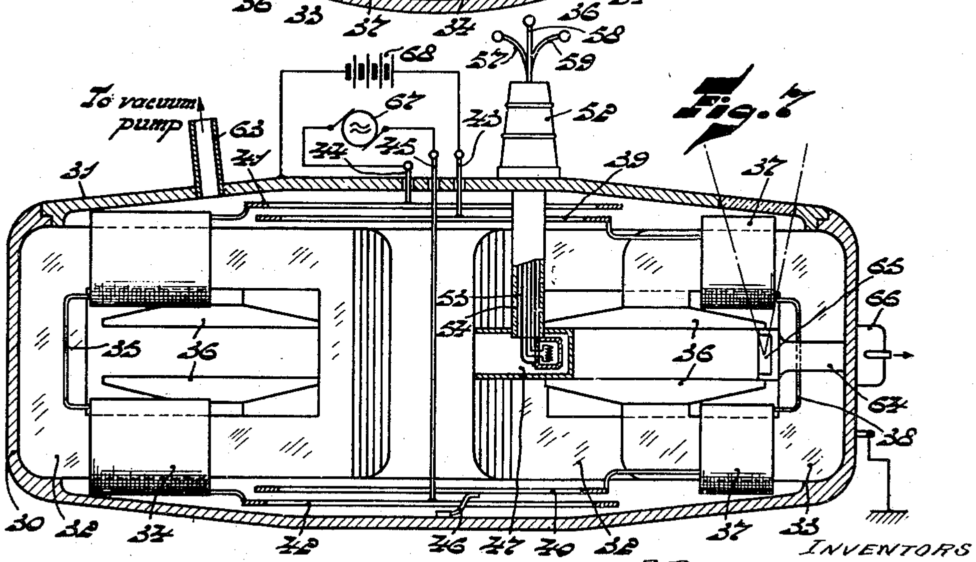


Fig. 7



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ELECTRIC DISCHARGE TUBE

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9 Claims. (Cl. 250—27)

Our invention relates to electric discharge tubes with Faraday electron acceleration.

X-ray tubes are known in which the electrons on their way from the cathode to the anode are accelerated, not by a voltage applied between two electrodes, but by an electric force induced in the discharge path itself. For this purpose an iron ring surrounds the discharge path and an alternating magnetic flux is generated in this ring by a coil through which an alternating current is passed. According to Faraday's law the variations of this flux (ϕ) with time (t) produce an electric force which is proportional to the differential quotient

$$\frac{d\phi}{dt}$$

It may therefore be said that in such a discharge tube there is a Faraday electron acceleration.

The well-known arrangement for securing such an electron acceleration comprises a transformer whose secondary winding is formed by the discharge path of the tube. The voltage induced in a single turn is only low, but the tube is constructed as a closed ring so that the electrons, after moving about the magnetic flux, again traverse the same path and thus increase their speed. After such circulations the electrons acquire a speed corresponding to the voltage set up in a secondary of n turns. To prevent the electrons from being hurled from the circular path due to their inertia, a magnetic transverse field is provided to impart to the electrons an acceleration directed towards the center of the ring. This ensures that the electrons pass many times around the magnetic flux in a spiral-shaped path until they impinge at a high speed upon the anode where they produce X-rays.

In tubes operating in the above manner, the speed of the electrons after one circulation only corresponds to the electro-motive force set up in a single turn, and consequently such tubes have the disadvantage that the number of circulations of the electrons must be very large before the electrons have a sufficient speed. For the same reason it has been useless to operate discharge tubes with rectilinear discharge paths in the above-mentioned manner, because the primary voltage must be extremely high to obtain a sufficiently high voltage in a secondary winding having only one turn.

Our invention enables to overcome the above disadvantages. One object of our invention is to increase the speed of the electrons during their passage through the induced electric field.

Another object of our invention is to construct in practice discharge tubes with Faraday electron acceleration without repeated circulation of the electrons.

A further object of our invention is to construct discharge utbes with Faraday electron acceleration with rectilinear discharge path.

Other objects of our invention will appear from the following description.

According to the invention we employ a device for Faraday electron acceleration in which the iron core is divided into a plurality of iron cores, and provide an energizing coil for each core.

If the core is divided into n parts, the speed of an electron corresponds to a voltage which is n times greater than that obtained in the well-known arrangement after one circulation. Thus, a voltage n times higher per circulation is set up in a tube closed in itself, and—assuming that the same primary voltages are used—a given speed can be obtained by giving the spiral-shaped part n times fewer turns, or an n times higher voltage can be obtained with the same number of circulations. The invention is a particular case of using a transformer in which the ratio between the secondary voltage V_2 and the primary voltage V_1 is

$$\frac{V_2}{V_1}=k\frac{n_2}{n_1}$$

In which k designates the number of iron cores forming the magnetic body of the transformer, and n_2 and n_1 designate the number of turns in the secondary and the primary windings respectively.

In order that the invention may be clearly understood and readily carried into effect we shall describe the same more fully with reference to the accompanying drawings in which,

Fig. 1 is a sectionalized diagrammatic view of a tube according to the invention in which the discharge beam has a rectilinear axis,

Fig. 2 is a section along line 2—2 of Figure 1,

Fig. 3 is a sectionalized diagrammatic view of a tube having a discharge path closed on itself,

Fig. 4 is a section through line 4—4 of Figure 3, and

Fig. 5 is a side-view of a portion of a discharge tube embodying the invention.

Fig. 6 is a section of a discharge device according to the invention the effective parts of which are all located in an evacuated space.

Fig. 7 is a section through line 5—5 of Fig. 6,

Fig. 8 is a section through a portion of the device shown in Figs. 6 and 7.

In Figs. 1 and 2, the reference numeral 1 indicates a high-vacuum discharge tube having an incandescible cathode **2** and an anode **4** directly connected together by a conductor **3**.

Surrounding the tube are a plurality of iron rings **5**, each of which is surrounded with a wire coil **6**. All the coils **6** are connected in a like sense in parallel across a source of alternating current **23**, shown as a generator. The cores **6** produce within the tube **1**, electric forces which are additive.

The electrons emitted by cathode **2** are moved into the path of the discharge by the electric field set up between the cathode **2** and the suction anode **27** by means of a source of E. M. F. shown as a battery **28**. Subsequently the electrons are propelled towards anode **4** by the resulting force, which is proportional to

$$k\frac{d\phi}{dt}$$

in which ϕ indicates the magnetic flux in one core and k the number of cores. When each of the coils **6** has n_1 turns and the voltage of source **23** is e_1 volts, the speed at which the electrons impinge on the anode **4** corresponds with the voltage

$$\frac{k}{n_1}e_1$$

If the same voltage were to be induced by a single primary winding surrounding all the cores, a k times larger primary voltage would have to be applied in order to pass the magnetizing current necessary for this purpose through this winding. In the tube according to the invention, the magnetizing current is supplied k times and the intensity of the same increases correspondingly, but a lower voltage can be applied to the primary windings.

In Figs. 3 and 4, reference numeral **7** designates a toroidal discharge tube having an incandescible cathode **8**, a collecting device **9** arranged towards the inner side of the tube, a suction anode **10** and a main anode **13**. An alternating voltage produced by a generator **24** is applied between cathode **8** and the apertured suction anode **10** arranged in front of the collecting device.

The tube is surrounded by a plurality of iron rings **12** provided with coils **11** which are energized by an alternating voltage in synchronism with the voltage produced by generator **24** so that the electric force brought about by the alternating magnetic field points in the direction of the cathode towards the suction anode during the half-cycles of the alternating current in which the suction anode **10** is positive with respect to cathode **8**. For this purpose the coils **11** may be connected in parallel across generator **24**.

To ensure that the electrons will circulate around the toroidal space of the tube numerous times before reaching the anode **13**, we provide a magnetic system having annular pole pieces **14** and **15** arranged within the tube (see Fig. 4). This system further comprises, pole pieces **25** provided with a coil **16** energized from a current source **26**, shown as a generator. Due to the division of the iron into k cores the voltage required for each of the coils **11** is again low. In addition, the increase in speed of the electrons may be substantially high for each circulation thereof than with the well-known tube comprising a simple primary so that fewer circulations are required to obtain a given speed.

If it is desired that the electrons flow in a circular path of constant diameter, we may use a magnetic longitudinal field which, as is well known, can influence the direction of flow of the electrons. In this case, we prefer to use the magnetic cores **12** as a winding for the magnet coil which causes the electrons to travel in a circular path. For this purpose, a construction such as shown in Figure 5 may be used.

In Figure 5 only a portion of the toroidal tube **7** of Figure 3 is shown. The tube is surrounded, in the manner shown in Figure 3, by a plurality of iron rings **17** which are slotted at **18**, and are provided with coils (not shown). The slots **18**, which are preferably so narrow that the resulting increase in reluctance of the magnetic circuit of the rings is no greater than in the case of butt joints used in transformers, produce two mutually-insulated ends on each of the rings **17**. The ends of adjacent rings are connected together by suitable metal strips **20** so as to electrically connect the rings as a solenoid. A direct current is passed through the rings by a suitable voltage supply (not shown) to produce within tube **7** a magnetic field which extends in the axial direction of the tube, in the present instance in a circle, and which causes the electrons to flow in the toroidal space within the tube.

A concentrating system such as shown in Figure 5 may, of course, be used with a linear tube such as shown in Figure 1, or in connection with tubes of other shapes.

The wave form of the energizing current of coil **16** should preferably be adapted to that of the energizing current of coils **11**.

With the methods known heretofore, using a similar principle, the electrons start at a speed substantially equal to zero or a constant speed. In these cases there is only one very small moment in which conditions are favourable for the electrons to reach the anticathode. Electrons starting before or after that moment meet a magnetic field of such a strength that it bends the path of the electrons so as to impinge on the tube wall.

Therefore we introduce a further degree of freedom by varying the initial velocity of the electrons, viz. applying a varying electron generating voltage between cathode **8** and anode **10**.

With such a system it is possible to adapt the voltage of generator **24** to the energizing current of coil **16** in such a way, that a substantially constant radius of the initial electron path is maintained during about 1/20 of a cycle. If need be the electron current may be cut off during the remaining part of the cycle, for example by applying a sufficiently negative potential to the focussing device **9** through wire **27**.

Generally speaking the value of the magnetic field between the pole pieces **14** and **15**, the voltage between the anode **10** and the cathode **8** and the radius of the circle on which the aperture of anode **10** is situated, should correlate in such a manner that the centripetal force on the electrons that have just passed through anode **8**, which force depends on the velocity of these electrons and the strength of the lateral magnetic field, is substantially equal to the force by which an electron having the said velocity is kept running in a circular path with a radius equal to the distance of the anode aperture from the centre of the circular system. During the course of the electron in the discharge path it is accelerated by the variable field of the cores **12**. If the lateral magnetic field would be constant, the centripetal force growing on only due to the increase of the tangential velocity of the electrons, would not be capable of keeping the electrons in a circular path. Consequently the path of the electron would be a spiral the radius vector of which would be about proportional to the electron velocity.

With a lateral magnetic field of varying strength it is possible to obtain a much steeper increase of the centripetal force, so that the increase of the radius of the electron paths is much smaller. Consequently a discharge device with a constant lateral magnetic field must have a considerably larger radial width than a device in which the lateral magnetic field is variable.

The magnetic force H, necessary for keeping an electron having a tangential velocity v in a circular path with a radius r is equal to

$$H=\frac{1703}{r}\beta\sqrt{(1-\beta^2)}\text{ gauss}$$

wherein $\beta=v/c$ and c is the velocity of light propagation.

This equation destines the voltage with which at a given magnetic force of the lateral field the electrons starting on a circular path are prevented from immediately deviating from this path.

Figs. 6 and 7 show a device according to the invention wherein the accelerating coils as well as the coils producing the Lorentz-force are enclosed in the vacuum. There is no separate toroidal tube as in the case of Figs. 3 and 4.

In a cylindrical housing 30 hermetically closed by a cover 31 there are mounted ring-shaped magnetic cores 32 of laminated iron, alternating with solid magnet bodies 33. Each of the cores 32 carries a set of two coils 34, connected in series by a wire 35. Cores 32 and coils 34 correspond with cores 12 and coils 11 of Fig. 3.

The magnet bodies 33 are provided with pole-shoes 36 between which a magnetic field may be produced having its lines of force parallel to the axis of the cylindrical housing. This magnetic field serves for producing the Lorentz-force that counteracts the centrifugal force of the electrons. Each of the magnet bodies 33 carries a set of two energizing coils 37, connected in series by a wire 38.

The sets of coils 37 are electrically connected to current leads 39 and 40 so as to be connected in parallel and the sets of coils 34 are connected likewise to current leads 41 and 42. Leads 39, 41 and 42 are provided with wires 43, 44 and 45, leading through the cover 31 in an insulated manner. Lead 40 is connected at 46 with the grounded housing 30.

Mounted in the housing is an electrode system construction 47, shown at an enlarged scale in Fig. 8. This system comprises a coiled filamentary cathode 48 surrounded by a focussing device 49. The latter is again mounted within a casing 50 having a slit 51 (shown in Fig. 6) and serving as an anode. The casing 50 is secured and electrically connected to the grounded cores 32. It is made of a non-magnetic metal and extends between two cooperating pole-shoes of one of the bodies 33.

Device 49 is supported from a high voltage insulator 52 by a metal tubular member 53, extending within a tubular member 54 of insulating material. Member 53 encloses wires 55 and 56 constituting the heating current supply leads of cathode 48. Wires 55 and 56 and member 53 are insulated from each other for low tension, but they are insulated from housing 30 for high tension. Three wires 57, 58 and 59 project from insulator 52 connected to wires 55 and 56 and to member 53 respectively. As shown in Fig. 8 wires 55 and 56 are connected to a source of heating current 60 for cathode 48, shown as a battery and wire 55 and member 53 are connected to the ends of a source of low tension, shown as a battery 61. By means of battery 61 focussing device 49 is made slightly negative with respect to the cathode. From the point of connection of wire 55 with batteries 60 and 61 a wire 62 leads to the negative terminal of a high voltage direct current generator (not shown) the positive terminal of which is grounded. The negative voltage supplied to the cathode 48 may be 100 kv. e. g.

In order to prevent break-down in the gap between device 49 and casing 50, housing 30 is highly evacuated. A connection for a high vacuum pump (not shown) is provided at 63.

Secured to the cylindrical wall of housing 30 is an anticathode 64 comprising a target 65 extending between the pole-shoes of one of the magnet bodies 33. Means are provided for supplying the anti-cathode with cooling liquid and indicated at 66.

The operation of the device is as follows: Wires 44 and 45 are connected to a source of current 67, producing alternating voltage of e. g. 500 cycles. Thereby an alternating magnetic field is produced in the cores 32.

Between wire 43 and the housing 30 a constant voltage is applied from a source 68. Thereby coils 37 are energized with direct current.

High voltage is applied between cathode 48 and anode 50, the anode being positive. This causes a beam of electrons emerging from the slit 51 of anode 50. The longer dimension of the slit is parallel to the cylinder axis of the housing and the shorter dimension is in the radial direction. Consequently a band shaped beam of electrons is produced having the longer side of its section directed parallel to the axis of housing 30.

Assuming the axial distance of slit 51 to be r and the velocity of the electrons emerging from slit 51 v, the magnetic field between pole-shoes 36, produced by the direct current is so established as to have strength

$$H=\frac{1703}{r}\beta\sqrt{(1-\beta^2)}$$

The electron then tends to follow a circular path with radius r.

Due to the varying magnetic field in the cores 32 a tangentially directed varying E. M. F. is produced by which the electrons are accelerated. This causes the radius of their path to increase, so that the electron paths take the form of a spiral, which causes the electrons to impinge on the target 65, provided the electrical values being properly chosen.

By the impingement of the electrons with high velocity, corresponding e. g. with a voltage of 1000 kv. very hard X-rays are generated. For the passage of a conical beam of X-rays in an axial direction a window 69 is provided in the cover.

The velocity of the electrons may be considerably increased because there are a plurality of accelerating coils provided and the action of all of these coils has a cumulative effect.

While we have described our invention in connection with certain applications and with reference to specific structural details, we do not desire to be limited thereto because obvious modifications will present themselves to one skilled in the art.

What we claim is:

1. In combination an electric discharge tube including means to produce a stream of electrons within the tube, and a device for producing Faraday acceleration of the electrons within the tube including a plurality of iron cores of annular shape surrounding said tube and each provided with a slot to form two mutually-insulated ends, an energizing coil for each core, means electrically interconnecting said cores in series to form a coil thereof, and means to pass a current through said cores to thereby produce a magnetic field within the tube and substantially coaxial therewith.

2. In combination an electron discharge device, a plurality of looped iron cores, an energizing coil on each core, said cores being so arranged as to enclose a ring-shaped space, an electrode system including a cathode and a perforated anode spaced apart so as to produce a beam of electrons emerging from said anode within said ring-shaped space in a tangential direction, means for producing a lateral magnetic field exerting on the electrons a centripetal force and an anticathode in said space for receiving the electrons accelerated by said cores when alternating current is supplied to said coils.

3. In combination an electron discharge device, a plurality of looped iron cores, an energizing coil on each core, said cores being so arranged as to enclose a ring-shaped space, an electrode system including a cathode and a perforated anode spaced apart so as to produce a beam of electrons emerging from said anode within said ring-shaped space in a tangential direction, means for producing a lateral magnetic field of varying strength, exerting on the electrons in said ring-shaped space a varying centripetal force and means for applying a varying electron genearting voltage between said cathode and anode.

4. In combination an electron discharge device a plurality of looped iron cores, an energized coil on each core, said cores being so arranged as to enclose a ring-shaped space, an electrode system including a cathode and a perforated anode cooperating with said cathode so as to produce a beam of electrons emerging from said anode within said ring-shaped space in a tangential direction, means for producing a lateral magnetic field of varying strength, exerting on the electrons in said ring-shaped space a varying centripetal force, means for applying a varying electron generating voltage between said cathode and anode and means for interrupting the beam of electrons during selected time intervals.

5. In an electron discharge device a plurality of looped iron cores, an energizing coil on each core, said cores being so arranged as to enclose a ring-shaped space, means for producing a beam of electrons in said space at a certain distance from the axis thereof in a tangential direction with an initial velocity, means for producing a magnetic field having the value whereby electrons having the initial velocity are caused to travel in a circular path having a radius equal to said distance.

6. In an electron discharge device a plurality of looped iron cores, an energizing coil on each core, said cores being so arranged as to enclose a ring shaped space, means for producing a beam of electrons in said space at a distance r from the axis thereof in a tangential direction, with a velocity v, means for producing a lateral magnetic field in said space of a strength H, whereby

$$Hr=1703\beta\sqrt{(1-\beta^2)_1}$$

β being the quotient between the velocity v and the light propagation velocity.

7. A hermetically closed vessel, a plurality of looped cores of laminated iron, an energizing coil on each core, said cores being so arranged as to enclose a ring-shaped space, first means for producing a tangentially directed beam of electrons in said space, second means for producing an axially directed magnetic field in said space and an anti-cathode mounted at the outer periphery of said space, means for highly evacuating said vessel and sources of voltage for energizing said coils and first means.

8. In combination an electric discharge device comprising an evacuated container, means for producing a beam of electrons in said container, and means for producing a varying magnetic field having lines of force encircling the electron beam to thereby produce Faraday acceleration of the electrons, said latter means comprising a large number of ring-shaped magnetizable cores surrounding the electron beam and a large number of energizing coils, each coil encircling the corresponding core to produce annular magnetic lines of force therein.

9. In combination an electric discharge device comprising an evacuated container, means for producing a beam of electrons in said container, and means for producing a varying magnetic field to thereby produce Faraday acceleration of the electrons, said latter means comprising a plurality of ring-shaped magnetizable cores surrounding the electron beam and an energizing coil for each of said cores, said coils being connected in parallel.

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