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(54) **X-ray tube apparatus.**

(57) An X-ray tube including a vacuum containment vessel (10), an anode (14) disposed within the vacuum containment vessel and which is stationary relative thereto, a cathode (65) disposed within the vacuum containment vessel in operative relationship with the anode, apparatus for rotating the vacuum containment vessel and the anode together relative to a fixed reference and relative to the cathode such that the cathode is stationary relative to the fixed reference.

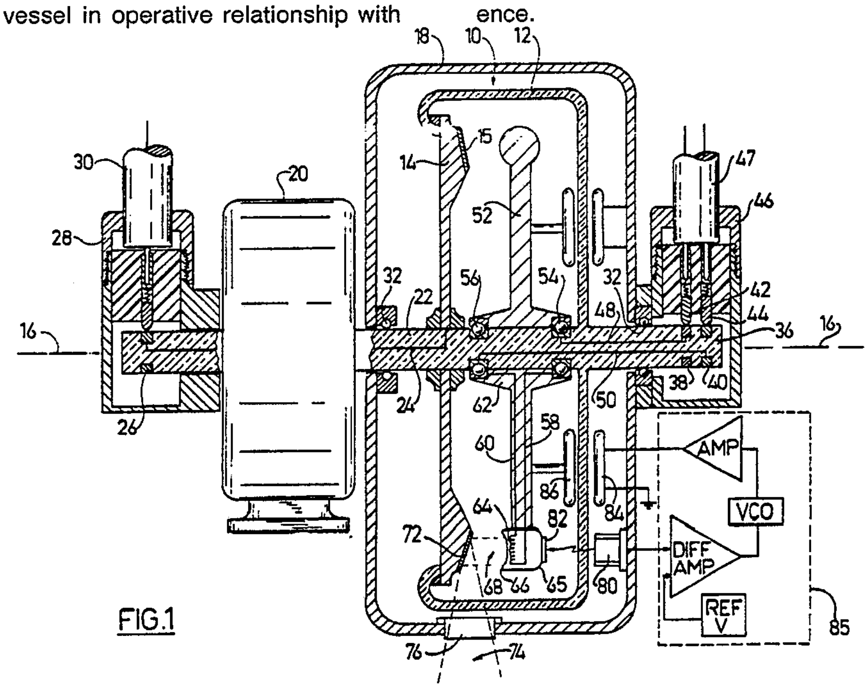

FIG.1

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FIELD OF THE INVENTION

The present invention relates to X-ray generation generally and more particularly to high power X-ray tubes suitable for medical applications.

BACKGROUND OF THE INVENTION

A great number of X-ray tube designs appear in the patent literature. The limiting parameter in many X-ray applications is the limited power output of the X-ray tube, both instantaneous and accumulated. This is so because, in typical high power X-ray tubes, the principal mechanism by which the anode can give off heat is by radiation since the anode is rotating at high speed in a relatively high vacuum and thus convection cooling thereof is not practical. Instantaneous and accumulated power limits of conventional rotating anode X-ray tubes are governed by the size of the anode, and more particularly its diameter and mass, the characteristics of the anode material, the rotational speed of the anode and the area of the focal spot thereon.

The focal spot is the area on the anode on which the electrons emitted from the cathode impinge. It is the footprint of the electron beam on the anode and is usually in the range of 0.5 to 10 mm^2. It is normally desired to minimize the area of the focal spot to improve resolution. The anode diameter, mass and rotational speed are limited by the mechanical forces involved in the rotation at speeds in the range of 3000 - 10,000 rpm of a considerable mass on vacuum bearings. Additional mechanical forces are encountered in computerized tomography (CT) applications wherein high centrifugal forces are present at right angles to the rotational axis of the anode.

There have been various attempts to solve the problem of convection cooling of a rotating anode by direct contact thereof with a flowing fluid. Two basic approaches have been followed:

In one approach a mechanism was proposed for convection cooling of a conventional rotating anode by means of internal fluid flow. In this approach, a problem lies in the vacuum sealing of rotational cooling fluid conduit connections extending between the rotating anode and a stationary heat exchanger.

U.S. Patents 4,577,340 and 4,625,324 to Carlson and Blaskis propose a rotating magnetic seal to permit fluid transfer between the rotating anode and an external heat exchanger through the anode shaft.

Another approach is to make the anode a part of a vacuum vessel which comes into contact with a cooling fluid at the outside thereof. Such an approach requires decoupling of the location of the electron beam focal spot, which must remain stationary, from the rotation of the vacuum vessel of which the anode forms a part.

U.S. Patent 2,493,606 to Waterton and U.S. Patent 4,250,425 to Gabbay et al attempt to achieve such decoupling by electromagnetic deflection of the electron beam which originates at a rotationally invariable center axis of an X-ray tube. This approach is limited by the difficulty of controlling the electron beam in the presence of strong cathode to anode fields.

A rotating cathode support is described in U.S. Patent 4,128,781 to Flisikowski et al. In this patent the ring anode is stationary and the X-ray beam is moving in space. This configuration is unsuitable for many X-ray applications wherein a stationary X-ray beam is required.

SUMMARY OF THE INVENTION

The present invention seeks to provide an X-ray tube which has greater output power than conventional X-ray tubes presently known due to its particular structure.

There is thus provided in accordance with a preferred embodiment of the present invention an X-ray tube including a vacuum containment vessel, an anode disposed within the vacuum containment vessel and which is stationary relative thereto, a cathode disposed within the vacuum containment vessel in operative relationship with the anode, apparatus for rotating the vacuum containment vessel and the anode together relative to a fixed reference and relative to the cathode such that the cathode is stationary relative to the fixed reference.

Additionally in accordance with a preferred embodiment of the invention a balanced cathode mounting member is provided for mounting of the cathode.

Further in accordance with a preferred embodiment of the invention, apparatus is provided for precisely controlling rotation of the cathode, and thereby the position of the focal spot, so as to maintain desired resolution. In accordance with one preferred embodiment of the invention, the cathode position is monitored with respect to a fixed reference and is adjusted as necessary by means of magnetic coupling across the vacuum containment vessel.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be understood and appreciated more fully from the following detailed description, taken in conjunction with the drawings in which:

Fig. 1 is a generalized illustration of an X-ray tube constructed and operative in accordance with a preferred embodiment of the present invention;

Fig. 2 is a generalized illustration of an X-ray tube of the type illustrated in Fig. 1 and including magnetic bearings;

Fig. 3 is a plan view of a cathode mounting member forming part of the apparatus of Fig. 2 taken along the direction indicated by arrow III on Fig. 2;

Fig. 4 is an electrical diagram of the current flow in the apparatus of Figs. 2 and 3;

Fig. 5 is a block diagram illustration of position and orientation control apparatus useful in the apparatus of Figs. 2 and 3;

Fig. 6 is a generalized illustration of another embodiment of an X-ray tube of the type illustrated in Fig. 1 and including magnetic bearings;

Fig. 7 is a plan view of a cathode mounting member forming part of the apparatus of Fig. 6 taken along the direction indicated by arrow VII on Fig. 6;

Fig. 8 is a generalized illustration of yet another embodiment of an X-ray tube constructed and operative in accordance with an embodiment of the present invention;

Fig. 9 is a partially sectional and partially planar illustration of a cathode mounting member forming part of the apparatus of Fig. 8 taken along the direction indicated by arrow IX in Fig. 8.

Figs. 10A, 10B and 10C are respectively a plan view of a cathode assembly useful in the apparatus 8 and two cross sections taken along the lines XB - XB and XC - XC respectively of Fig. 10A;

Fig. 11 is a generalized illustration of yet another embodiment of X-ray tube constructed and operative in accordance with a preferred embodiment of the present invention; and

Fig. 12 is a plan view of a cathode mounting member forming part of the apparatus of Fig. 11 taken along the direction indicated by arrow XII on Fig. 11.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Reference is now made to Fig. 1, which illustrates an X-ray tube constructed and operative in accordance with a preferred embodiment of the present invention. A vacuum containment vessel 10, typically comprising a glass envelope 12 sealingly attached to an anode disk 14, typically formed of copper or graphite and having brazed thereon an annular anode surface 15 of tungsten or any other high Z refractory material, has an overall disk-like configuration and is driven for rotation about an axis 16 relative to a fixed housing 18, typically formed of metal, by means of an electric motor 20 via a drive shaft 22, formed of an electrical insulator. Vacuum sealing of the metal and glass elements of vessel 10 is achieved by techniques known to the art.

A high tension voltage lead 24 to the anode disk 14 is typically embedded in the drive shaft 22 and receives a desired voltage supply via a slip ring assembly 26, which is in turn connected via a connector 28 and a cable 30 to the positive terminal of a high voltage generator (not shown).

Electric motor 20 and housing 18 are fixedly mounted onto an external support surface (not shown), defining a reference position and direction relative to which the X-ray beam is aimed. The interior of housing 18 outside of vacuum containment vessel 10 is filled with a cooling and isolating fluid. Leakage of the fluid outside of housing 18 is prevented by fluid sealing bearings 32, which engage the drive shaft 22 at both sides of the housing 18.

At the opposite side of the housing 18 from motor 20, the drive shaft engages a second slip ring assembly 36, which is a dual slip ring, engaging a pair of ring contacts 38 and 40 on the drive shaft 22. The slip ring assembly 36 includes a pair of spring loaded contacts 42 and 44 which engage respective rings 38 and 40 and are connected via a connector 46 and a cable 47 to the negative terminals of a high voltage generator (not shown). Embedded within drive shaft 22 are conductors 48 and 50 which connect the rings 38 and 40 with the inner races of a pair of bearings 54 and 56 respectively.

A precisely balanced cathode carrier member 52 is bearing mounted within vacuum containment vessel 10 with respect to shaft 22 by means of bearings 54 and 56. Conductors 48 and 50 establish electrical contact with corresponding conductors 58 and 60 via bearings 54 and 56 respectively.

The cathode carrier member 52 is formed with a relatively wide center section 62, disposed between bearings 54 and 56, in order to provide stability and positional controllability under strong axial and radial accelerations encountered during operation of the X-ray tube. A cathode filament 64 forming part of a cathode assembly 65, is connected between the conductors 58 and 60 completing the cathode current circuit. Focusing cup 66 is negatively biased relative to the average filament voltage of filament 64 by being connected to the more negative side of the filament.

As in a conventional X-ray tube, the filament 64 and focusing cup 66 produce an electron beam 68, which strikes the anode surface 15 at a location 72, which is usually referred to as the "focal spot". An X-ray beam 74 is thus produced and is projected through a low absorption window 76 of housing 18 for impingement upon a desired location, such as a medical subject. According to an alternative embodiment of the invention, multiple cathodes, each of which may be adapted for a different X-ray beam application, may be arranged on the cathode carrier member 52 in such a manner that they can be selectably employed by rotating the cathode carrier member 52 until a different cathode is positioned in cooperative registration with the beam window 76. Filament current is then routed to the selected cathode by a suitable switch (not shown), preferably a non-contacting magnetic switch operated by a magnetic actuator located outside the vacuum vessel 10.

It is appreciated that, in addition to being formed of a material having high thermal conductivity, anode disk 14 is configured to maximize heat transfer from disk to the surrounding cooling fluid exterior of vacuum containment vessel 10 and may be formed with suitable fins which enhance cooling fluid flow and turbulence through centrifugal agitation of the fluid.

In order to provide desired high resolution, the position of the cathode, and thus of the focal spot of the electron beam on anode surface 15 must be precisely controlled preferably to a tolerance of 0.1 mm. For this purpose, an optical sensor 80 is provided to sense a reference marking on a reflector 82 fixedly associated with the cathode assembly 65. Optical sensor 80 is fixed onto housing 18, which is fixedly mounted onto a reference surface. Selected rotation of the cathode assembly 65 relative to the vessel 10 is provided in response to the sensed position of the cathode assembly by means of field inducing coils 84 which are fixedly mounted inside of enclosure 18 and rotating field coils 86, which are mounted interior of vessel 10 and fixed to cathode carrier disk 52 in generally facing and inductive relationship with coils 84.

The operation of the apparatus of Fig. 1 will now be described briefly: Electric motor 20 rotates the vacuum containment vessel 10 about axis 16 at a typical speed of 100 -10,000 RPM. The bearing mounting of cathode carrier member 52 onto drive shaft 22 prevents most of the rotation from being transmitted to the cathode carrier disk. However, frictional forces through bearings 54 and 56 do produce some torque.

This torque is countered by a counter torque produced by interaction of coils 84 and 86 in much the same way as a conventional brushless AC servo motor operates when adapted to provide position control. The counter torque is produced by coils 84 which generate a rotating magnetic field whose frequency is controlled by a servo system 85 of conventional design which receives an output from optical sensor 80 and provides position control of cathode carrier member 52 by adjusting the rotational frequency of the field so that the forces induced by friction through bearings 54 and 56 are exactly canceled by opposite forces generated by the rotation of the field relative to coils 86. Thus the focal location 72 remains precisely stationary with respect to the enclosure 18.

Reference is now made to Figs. 2 and 3 which describe an embodiment of the invention employing magnetic bearings and contactless current flow. In comparison with the embodiment of Fig. 1, it can be seen that mechanical bearings 54 and 56 of the embodiment of Fig. 1 are replaced in the embodiment of Figs. 2 and 3 by magnetic bearings and thermionic diodes as will be described in detail hereinbelow.

An external electric motor (not shown) is provided having a drive shaft 122 formed of an electrical insulator, such as glass or ceramic, in which are embedded cathode and filament current supply leads 148 and 150. The external electric motor and a tube housing 160, typically formed of metal, are fixedly mounted onto an external support surface (not shown) by suitable brackets (not shown). Drive shaft 122 passes through a wall of housing 160 via fluid sealing bearings 132. Fixedly mounted onto drive shaft 122 for rotation together therewith is a vacuum containment vessel 110, typically a two part glass envelope comprising portions 111 and 112 which are joined by an anode ring 114.

Rotatably mounted within vacuum containment vessel 110 so as to remain relatively stationary relative to the external support surface notwithstanding high speed rotation of vessel 110 is a cathode carrier member 152. Mounting of the cathode carrier member 152 is by means of magnetic bearings, which will be described hereinbelow. A detailed description of the use of magnetic bearings in an X-ray tube appears in U.S. Patent 4,322,624, the disclosure of which is incorporated herein by reference. Back-up mechanical bearings 169 are also provided. Mechanical bearings 169 are normally not contacting but operate only when the magnetic bearings are inoperative, such as during shifting of cathodes as will be described hereinbelow or in the case of malfunction of the magnetic bearings. In such instances, the mechanical bearings 169 limit the displacement of the cathode carrier disk 152 both axially and radially.

Mounted onto the cathode carrier member 152 are a plurality of cathode assemblies 188, each typically including a filament 163 and a focusing cup 164. For illustration, an embodiment having six such cathode assemblies is shown.

Electrical current is transmitted selectably to each cathode assembly 188 by a contactless technique employing thermionic diodes as will now be described. The use of such contactless techniques in X-ray tubes is described, inter alia, in U.S. Patents 4,679,220; 4,651,336; 4,417,171 and 4,414,681, the disclosures of which are incorporated herein by reference.

The current flow in the apparatus of Figs. 2 and 3 will now be described in detail with reference to Fig. 4.

Current for the cathode filament 163 is drawn from a high tension power supply (not shown) via a connector 158. Leads 136 and 154 connect connector 158 to a dual slip ring assembly 151, which brings leads 136 and 154 into permanent rotating electrical contact with leads 148 and 150 respectively.

Lead 148 is held at a more negative potential than lead 150. Lead 148 is connected in series to lead 150 via a filament 153, a resistor 155 and a filament 157. Filaments 153 and 157 are carried on drive shaft 122 inside the rotating vacuum containment vessel 110 and are stationary relative thereto.

Current passing filaments 153 and 157 provides heating thereof. Filament 153 cooperates with an annular anode 170 in order to generate a non-contacting thermionic current flow wherein anode 170 has a potential which is similar to the potential of lead 148. Filament 157 indirectly heats a surface treated annular cathode 159, which may be barium impregnated or oxide coated, and produces electron emission therefrom.

Electrons emitted by cathode 159 are collected by an annular anode 161, which is perforated or otherwise adapted to allow heat radiated from the filament 157 to heat the cathode 159. Similar indirect heating arrangements are described, inter alia in U.S. Patents 4,414,681; 4,679,220 and 4,651,336. The current flow from cathode 159 to anode 161 makes the potential of the cathode 159 similar to the potential of lead 150 to which anode 161 is electrically connected.

Accordingly a potential difference is established between anode 170 and cathode 159, both of which are mounted on the cathode carrier member 152 concentric with the rotational axis thereof.

The electron current collected at anode 170 is fed through a lead 168 and a magnetic switch 174 to the cathode filament 163 and back through lead 166 to the cathode 159. Both leads 166 and 168 are embedded in the cathode carrier member 152.

A switch 174 is operated by magnetic induction from an electromagnet 176 located outside the rotating vacuum containment vessel 110 in a fixed position relative to a radiation window 182 formed in vessel 110. The switch 174 is operative to route the current flowing between anode 170 and cathode 159 through a given cathode assembly selected from among the plurality of cathode assemblies 188 to be currently positioned adjacent the radiation window 182.

Resistor 155 is chosen in relation to the resistances of the remaining components in the circuit of Fig. 4 so that a wide range of electron current levels are emitted from the filament 163 in response to a suitable change in the potential differences between leads 148 and 150.

Alternatively, resistor 155 can be replaced by suitable means for independently controlling the current passing through resistors 153 and 157. In this case, two additional leads from the high tension power supply to the slip ring assembly 151 and two additional ring contacts are required. The two additional contacts, designated T2 and T3 on Fig. 4 are connected to filaments 153 and 157 respectively as shown in dashed lines in Fig. 4, and resistor 155 is eliminated. The potentials of contact T2 relative to contact T4 and of contact T3 relative to contact T1 are chosen to provide the desired electron emissions from filaments 153 and 157 respectively.

Thermonically emitted electrons 181 from filament 163 are accelerated towards anode ring 114 and impinge on a focal point track 180 defined thereon and typically formed of a high Z temperature resistant metal such as tungsten. An X-ray beam 197 is generated thereby and is projected through a window 182 formed in housing 160 onto an examination subject.

The anode current from anode ring 114 is carried away by a rolling contact 184 which is urged by a spring 186 into electrical engagement with the outside surface of anode ring 114. The rolling contact 184 is electrically coupled by the spring conductor 186 to connector 189 and thereby to the high tension power supply. This arrangement effectively forms a slip ring comprising parts 114, 184 and 186.

Heat from the anode ring 114 is carried away by direct contact between an outside surface of anode ring 114 with a cooling and electrically insulating liquid which fills the inside of housing 160 outside of vacuum containment vessel 110. The outside surface of anode ring 114 may advantageously be formed with vanes, funnels or other surface conditioning which encourages a turbulent flow of cooling fluid through centrifugal agitation of the liquid. The liquid also cools and lubricates the rolling contact 184.

It may be desirable to provide a non-contacting current transmission path for discharging electrostatic potential from the surface of the cathode carrier member 152. Such a path, not shown, may be provided similarly to the current transmission path described above in detail for supplying current to the cathodes 188. A mechanism of this type is described in U.S. Patents 4,417,171 and 4,679,220 which have been incorporated herein by reference.

In order to position and azimuthally orient the cathode carrier member 152, the magnetic bearings preferably comprise six independently controllable electromagnets which cooperate with the cathode carrier member 152 for maintaining it in a desired orientation. In the illustrated preferred embodiment, there are provided three independently controllable electromagnets 200 fixedly mounted with respect to the housing 160 adjacent the periphery of the cathode carrier member 152 and three independently controllable electromagnets 206 fixedly mounted with respect to housing 160 adjacent the cathode carrier member 152 at the central region thereof.

Electromagnets 200 are generally distributed about the azimuth with a 120 degree separation therebetween as are electromagnets 206.

Arranged for operative engagement with electromagnets 200 are six discrete magnetically soft elements 240 which are fixedly mounted in a generally uniform azimuthal distribution onto the oathode carrier member 152 with a 60 degree separation therebetween. At any given time during operation of the magnetic bearings, three of the elements 240, separated from each other by 120 degrees, are magnetically retained in registered engagement with corresponding electromagnets 200, while the remaining three elements 240 are disposed therebetween, and generally evenly separated from the electromagnets in azimuth by 60 degrees.

Similarly, there are arranged for operative engagement with electromagnets 206 six discrete magnetically soft elements 250 which are fixedly mounted in a generally uniform azimuthal distribution onto the cathode carrier member 152 with a 60 degree separation therebetween. At any given time during operation of the magnetic bearings, three of the elements 250, separated from each other by 120 degrees, are magnetically retained in registered engagement with corresponding electromagnets 206, while the remaining three elements 250 are disposed therebetween, and generally evenly separated from the electromagnets in azimuth by 60 degrees.

The position and orientation of the cathode mounting member 152 for six degrees of freedom is actively stabilized by continuously adjusting the forces and momenta exerted by electromagnets 200 and 206 on the magnetically soft elements 240 and 250. These forces and momenta are adjusted by adjusting the currents flowing through the windings of the electromagnets 200 and 206 using a control processor 210 typically of a type illustrated in Fig. 5.

Control processor 210 continuously monitors the position and orientation of the cathode mounting member 152 through six optical sensors 190 which detect the reflected radiation of six beams produced by six light sources 192 at six reference locations 194 on cathode mounting member 152.

Each optical sensor 190 is adapted to measure the displacement of a corresponding reference location 194 in a particular direction. The positions of the sensors 190 and the locations 194 are chosen in a geometrical arrangement that allows the measurement of all six degrees of freedom of the cathode carrier member 152 through sensing the outputs of all six sensors 190.

This arrangement of magnetic bearings and position control is essentially similar to the arrangements described in the above referenced patents, except that unlike the conventional rotating anode arrangement where only five degrees of freedom are controlled, in this arrangement, the azimuthal orientation of the cathode carrier member 152 relative to the rotational axis 16 is also controlled.

Alternatively, some degrees of freedom can be restricted by suitable adaptation of the design of the magnetic bearings such that in some directions the desired position of the cathode carrier member 152 is stable by virtue of the magnetic field configuration. This technique is also described in the above referenced patents and it enables replacement of some of the electromagnets and some of the sensors with static permanent magnets.

The selection of which elements 240 and 250 engage which respective electromagnets 200 and 206 determines which of cathodes 188 is located in operative engagement with window 182. This selection is preferably achieved through the use of two sets of three auxiliary electromagnets associated with elements 240. A first set of three electromagnets 260 is arranged in generally the same plane as electromagnets 200 and is arranged such that the electromagnets 260 are uniformly separated by 120 degrees and are angularly offset from electromagnets 200 by 40 degrees in the counterclockwise direction in the sense shown in Fig. 3. A second set of three electromagnets 266 is arranged in generally the same plane as electromagnets 200 and 260 and is arranged such that the electromagnets 266 are uniformly separated by 120 degrees and are angularly offset from electromagnets 200 by 40 degrees in the clockwise direction in the sense shown in Fig. 3.

Rotation of the cathode carrier member 152 is effected by temporarily de-energizing electromagnets 200, while, at the same time, energizing electromagnets 260, thus producing a 20 degree clockwise azimuthal rotation of cathode carrier member 152 in the sense of Fig. 3. A further 20 degree clockwise azimuthal rotation of cathode carrier member 152 in the sense of Fig. 3 is provided by subsequent de-energization of electromagnets 260 and corresponding energization of electromagnets 266. An additional 20 degree clockwise azimuthal rotation of cathode carrier member 152 in the sense of Fig. 3 is produced by de-energization of electromagnets 266 and corresponding energization of electromagnets 200.

During rotation of the cathode carrier member 152 and the required de-energization of electromagnets 200, the cathode carrier member 152 may be supported on the back-up mechanical bearings 169.

Alternatively, rotation of the cathode carrier member 152 can be effected by an arrangement similar to a conventional stepper motor. The stator of the motor replaces the electromagnets 260 and 266 and the rotor is fixedly attached to the cathode carrier 152. The rotor can be integrated with the magnetic element 240 or alternatively it may comprise a separate element.

It is important to note that the stepwise rotation mechanism of the cathode carrier member 152 essentially replaces the induction motor used in conventional rotating anode tubes to effect the continuous rotation of the anode. Thus many anode bearing designs used for conventional X-ray tubes can be adapted for the support of a stationary cathode carrier member 152 within a rotating vacuum vessel 110 by replacing the conventional induction motor with a suitable servomotor or stepper motor.

According to an alternative embodiment of the invention, rotation of the cathode carrier member 152 may be effected without requiring use of auxiliary electromagnets by allowing the mechanical back-up bearings 169 to momentarily engage the cathode carrier member 152 when the magnetic bearings are temporarily de-energized. This momentary engagement imparts angular rotation to the cathode carrier member 152 by virtue of rotation of the vacuum containment vessel 110. As a further alternative, the rotation of the cathode carrier member 152 may be produced by induction coils which provide a rotating magnetic field and field coils which are attached to the cathode carrier member and move in response to the thus induced field. Such an embodiment is illustrated in Fig. 1.

Electrical power is supplied to the filament 163 of the cathode assembly 188 which is positioned in operative engagement with window 182 by means of magnetically operated switch 174, associated with that filament which is operated by an electromagnet 176. Thus, it may be appreciated that as a given cathode assembly 188 is positioned in association with window 182, its corresponding switch 174 is positioned so as to be operated by electromagnet 176.

Reference is now made to Figs. 6 and 7 which illustrate a further alternative embodiment of the invention which produces an axial beam. The embodiment of Figs. 6 and 7 is similar to the embodiment of Figs. 2 - 5 except for geometrical differences associated with the differences in the mechanisms required to generate an axial X-ray beam rather than a radial beam. Elements in the embodiment of Figs. 6 and 7 which are identical or similar in function to those in the embodiment of Figs. 2 - 5 are identified by identical reference numerals.

Principal differences between the embodiment of Figs. 6 and 7 and that of Figs. 2 - 5 include the following:

The cathode assemblies 188 project radially from the cathode carrier member 152 and face an annular anode ring 114 having a tungsten beam track 180 disposed on the inward face thereof. The electron beam generated by the cathode assembly 180 is radially directed and the X-ray beam emerges parallel to the rotational axis of the tube.

Reference is now made to Figs. 8 - 10, which illustrate a further alternative embodiment of X-ray tube constructed and operative in accordance with a preferred embodiment of the present invention. In this embodiment, the cathode current is supplied by a beam of electrons which emerge from a location along the rotational axis of the X-ray tube which is stationary under rotation. The beam of electrons is deflected electromagnetically towards a cathode which is located on a rotating cathode mounting member. The cathode comprises a high emissivity material so as to produce a cloud of electrons through the combined effects of thermal emission and secondary electron emission.

Electrons from the electron cloud are attracted towards the anode through a narrow slit in the cathode face and are focused onto a focal spot by the configuration of the cathode face.

It is a particular feature of this embodiment that, unlike previous attempts to aim an electron beam at a rotating anode such as described in U.S. Patent 2,493,606, the electron beam impinging on the cathode need not be particularly carefully focused and shaped. The electron beam travels completely inside an electrostatically shielded volume wherein the relatively strong field of the anode is not present. Accordingly a relatively simple focusing and deflection assembly may be employed for directing the electron beam to the cathode.

With particular reference to Fig. 8, it is seen that the X-ray tube comprises a housing 160, typically formed of metal, onto which is mounted an electric motor 402, by means of a mounting bracket 404. The electric motor 402 has a drive shaft 406 onto which is fixedly mounted a rotating vacuum containment vessel 110 comprising a rotation shaft portion 122, typically formed of a dielectric material, which is preferably integrally formed with an envelope portion 111. An anode ring 114 is sealingly connected between envelope portion 111 and a cap portion 112. Envelope portion 111 and cap portion 112 are typically formed of glass, while anode ring 114 is formed of a good heat and electricity conducting medium such as copper or brass.

Drive shaft 406 extends through a wall of housing 160 via fluid sealing bearings 132. A plurality of electrical leads, typically including leads 150, 148, 424 and 425 are embedded in rotation shaft portion 122 and communicate electrically via a slip ring assembly 151 and a cathode cable connector 158 with exterior electrical power sources (not shown).

An electron beam producing filament 153 is electrically connected at one end thereof by lead 424 to a terminal T2 on slip ring assembly 151. The opposite end of filament 153 and a focusing cup 436 are electrically connected by a lead 148 to a terminal T4 on the slip ring assembly 151. Filament 153 and focusing cup 436 operate in a conventional manner to provide a beam of electrons, indicated by reference numeral 438.

Lead 150, connected to terminal T1 of the slip ring assembly 151, establishes a positive electron beam accelerating potential on a Pierce gun dynode or accelerator 440 relative to the filament 153.

The electron beam 438 is magnetically deflected by a set of deflection coils 426 located in the volume between the outside of the vacuum vessel 110 and the housing 160. The coils 426 are fixedly mounted to the inside of the housing 160 and produce a magnetic field adapted to deflect the electron beam 438 in a plane fixed relative to the housing 160 and fixed relative to a magnetically supported cathode mounting member 152.

The cathode mounting member 152 carries a plurality of cathodes 188 of which only one lies in the trajectory of the deflected beam 438 at any given time. This cathode will hereinafter be termed the "active" cathode. The active cathode is selected for production of X rays by rotating the cathode mounting member 152 until the active cathode intersects the electron beam 438.

The electron beam 438 enters a receptor cup 442 of the active cathode 188, producing an electron cloud as mentioned above. A secondary electron beam 181 emerges from a slit 441 formed in the cup 188 and impinges on the anode 114 at a focal spot 180 and thus generates an X-ray beam 197 which is projected through a window 182 in the housing 160 so as to impinge on an examination subject.

As noted hereinabove, the X-ray generating beam 181 is generated by thermionic and secondary emissions of electrons in the receptor cup 442. By suitable selection of the geometry of the cup, the material of which it is formed and the potential at which it is maintained, it is possible to achieve a wide range of ratios between the primary electron beam 438 and the secondary electron beam 181.

The potential of the cathodes 188 has to be kept positive relative to the filament 153. This is achieved by providing a non-contact current flow mechanism between the cathode 188 and the Pierce gun accelerator 440. The mechanism comprises an annular cathode 159, suitably treated for high emissivity, a heating filament 157 and the accelerator 440, which serves as an anode, all disposed concentrically about the rotational axis 16 of the tube.

The filament 157 is connected at one end thereof via a lead 425 to terminal T3 on the slip ring assembly 151 and on its other end to the accelerator 440. A voltage difference between T3 and T1 is chosen to heat the filament 157 to a temperature suitable to induce thermal emission from the cathode 159 thus making its potential substantially similar to the potential of accelerator 440. The cathodes 188 are electrically connected to the cathode 159 by a conductive film deposited on the inside surface of the cathode mounting member 152. The film also produces a shielding effect in the vicinity of the trajectory of the electron beam 438. The electrical circuit thus produced is substantially similar to the corresponding circuit illustrated in Fig. 4, having terminals T1, T2, T3 and T4. Dashed lines indicate leads 424 and 425. The receptor cap 442 replaces elements 170, 168, 174 and 163 and the accelerator 440 functions as the anode 161.

According to an alternative embodiment of the invention and similarly to the structure of the embodiments of Figs. 2 - 7, terminals T2 and T3 may be eliminated by interconnecting leads 424 and 425 via a suitably chosen resistor such as resistor 155 shown in Fig. 4.

Magnetic bearings support the cathode mounting member 152 in a desired position and orientation with respect to vacuum containment vessel 110 and with respect to anode 114. These bearings are substantially similar to the arrangement employed in the embodiments of Figs. 2 - 5 and Figs 6 - 7. Similar reference numerals indicate similar elements having similar functions in the operation of the bearings. This is also true for the position sensing mechanism and the control circuit employed in the embodiment of Figs. 8 - 10.

As in the above-described embodiments, the six optical sensors 190 monitor the position and orientation of the cathode mounting member 152 by detecting the reflection of radiation beams produced by sources 192 from reference locations 194. The six output values are used by a processor 210 to adjust the currents flowing through the six electro-magnets 200 and 206. Thus the attraction forces between the electro-magnets and corresponding magnetically soft element 240 and 250 are varied until the cathode mounting member 152 is positioned and oriented in the desired location and orientation.

The process of control is continuous, quickly correcting any displacement. Selection of the active cathode 188 is achieved by rotation of the cathode mounting member 152, which may be similar to the cathode selection operation described above in connection with the embodiments of Figs. 2 - 5 and 6 - 7. Two sets 260 and 266, each containing three auxiliary electro-magnets, produce stepwise rotation of the cathode mounting member 152 by sequential energization and de-energization as described above. The selection of an active cathode 188 in this embodiment does not require the use of a magnetic switch as selection is achieved simply by placing the desired cathode 188 in a position to intercept the electron beam 438.

Alternatively, a two dimensional deflection system can be employed, using orthogonal sets of deflection coils, which enable the deflection of the beam 438 towards the receptor cup 442 of each cathode 188 without rotation of the cathode mounting member 152. In this alternative embodiment a plurality of beam windows 182, each associated with a particular cathode 188, are disposed on the housing 160. A change of the selected active cathode 188 is effected by suitable rotation of the beam deflection plane relative to the housing 160, simultaneous with a counter-rotation of the housing 160 relative to its mounting surface that brings the newly selected cathode and its associated beam window into the same spatial position as the previous one.

It should be noted that this alternative is also applicable to the embodiments of Figs. 2 - 5 and Figs. 6 - 7 where it also eliminates the need for auxiliary stepping electro-magnets 260 and 266. In the embodiments of Figs. 2 - 5 and Figs. 6 - 7 however, this alternative requires the use of multiple magnetic actuators 176 each associated with a particular magnetic switch 174 and a particular cathode 188. Selection of an active cathode is thus effected by energizing one of the actuators 176 causing closure of the magnetic switch 174 associated with that cathode and thus connecting the selected cathode 188 to the current circuit.

Returning to the embodiment of Fig. 8, it is seen that the anode current is typically carried away by a spring loaded contact 186 having a contact ball 184 via an anode cable connector 189. The contact ball is lubricated and cooled by a cooling and electrically insulating fluid which fills the housing 160 outside of vacuum containment enclosure 110. This fluid importantly also cools the ring anode 114 by direct convection. The convection cooling may be further enhanced by the definition of vanes and funnels on the outside of the anode 114 which produce turbulent flow of the fluid through centrifugal agitation thereof.

Reference is now made to Figs. 11 and 12 which illustrate an embodiment operative to generate an axial X-ray beam. This embodiment is essentially similar to the embodiment of Figs. 8 - 10 except for geometrical differences associated with the generation of an axial X-ray beam rather than a radial beam. Elements in the embodiment of Figs. 11 and 12 which are identical or similar in function to those in the embodiment of Figs. 8 -10, are identified by identical reference numerals. In general the embodiment of Figs. 11 and 12 relates to the embodiments of Figs. 8 - 10 in a similar way as the embodiment of Figs. 6 - 7 relates to the embodiments of Figs. 2 - 5.

It should also be noted that the embodiment of Fig. 1 can be adapted to produce an axial rather than radial beam in much the same way as the embodiment of Figs. 2 - 5 is adapted in the embodiment of Figs. 6 - 7 and the embodiment of Figs. 8 - 10 is adapted in the embodiment of Figs. 11 and 12.

It will be appreciated by persons skilled in the art that the invention is not limited to the particular types of symmetries shown above or to the particular configurations of magnetic bearings or designs of position sensing mechanisms. Various cathode carrier member rotation and cathode switching arrangements other than the ones described above may be employed as may alternative current flow configurations. It is particularly noted that the mechanical control and position sensing apparatus described in the prior art references mentioned above for anode position control may be employed in whole or in part in the present invention for cathode position control. The teachings of these prior art references are incorporated herein by reference.

It will be appreciated by persons skilled in the art that the present invention is not limited to what has been particularly shown and described hereinabove. Rather the scope of the present invention is defined only by the claims which follow:

Claims

1. An X-ray tube comprising:
a vacuum containment vessel;

an anode associated with the vacuum containment vessel and which is stationary relative thereto;
a cathode disposed within the vacuum containment vessel in operative relationship with the anode; and
means for rotating the vacuum containment vessel and the anode together relative to a fixed reference and relative to the cathode such that the cathode is stationary relative to the fixed reference.

2. Apparatus according to claim 1 and also comprising rotatable means for mounting of the cathode relative to the anode.

3. Apparatus according to claim 1 or claim 2 and also comprising means for precisely controlling orientation of the cathode relative to the fixed reference.

4. Apparatus according to claim 3 and wherein said means for precisely controlling includes means for monitoring the cathode position with respect to a reference.

5. Apparatus according to claim 3 or claim 4 and wherein said means for precisely controlling includes means for magnetic coupling across the vacuum containment vessel.

6. Apparatus according to any of the preceding claims and wherein said cathode is mounted on mechanical bearings.

7. Apparatus according to any of the preceding claims 1 - 6 and wherein said cathode is mounted on magnetic bearings.

8. Apparatus according to claim 2 and wherein said rotatable means comprise means for mounting a plurality of cathodes.

9. Apparatus according to claims 3 and 8 and wherein said means for precisely controlling includes means for selecting an active cathode from among said plurality of cathodes.

10. Apparatus according to any of the preceding claims and comprising means for direct convection cooling of said anode surface.

11. Apparatus according to claim 10 and wherein said means for direct convection cooling comprises means for providing a coolant liquid in direct contact with said anode.

12. Apparatus according to any of the preceding claims and also comprising non-contact current flow generation means for providing electrical current to said cathode.

14. Apparatus according to claim 12 and wherein said non-contact current flow generation means includes magnetic deflection means for providing a directed flow of electrons to said cathode.

15. Apparatus according to claim 14 and wherein said cathode is operative in response to impingement thereon of said directed flow of electrons to provide a secondary flow of electrons.

16. Apparatus according to claim 15 and wherein said cathode is operative to focus said secondary flow of electrons onto said anode for producing X ray emissions thereat.

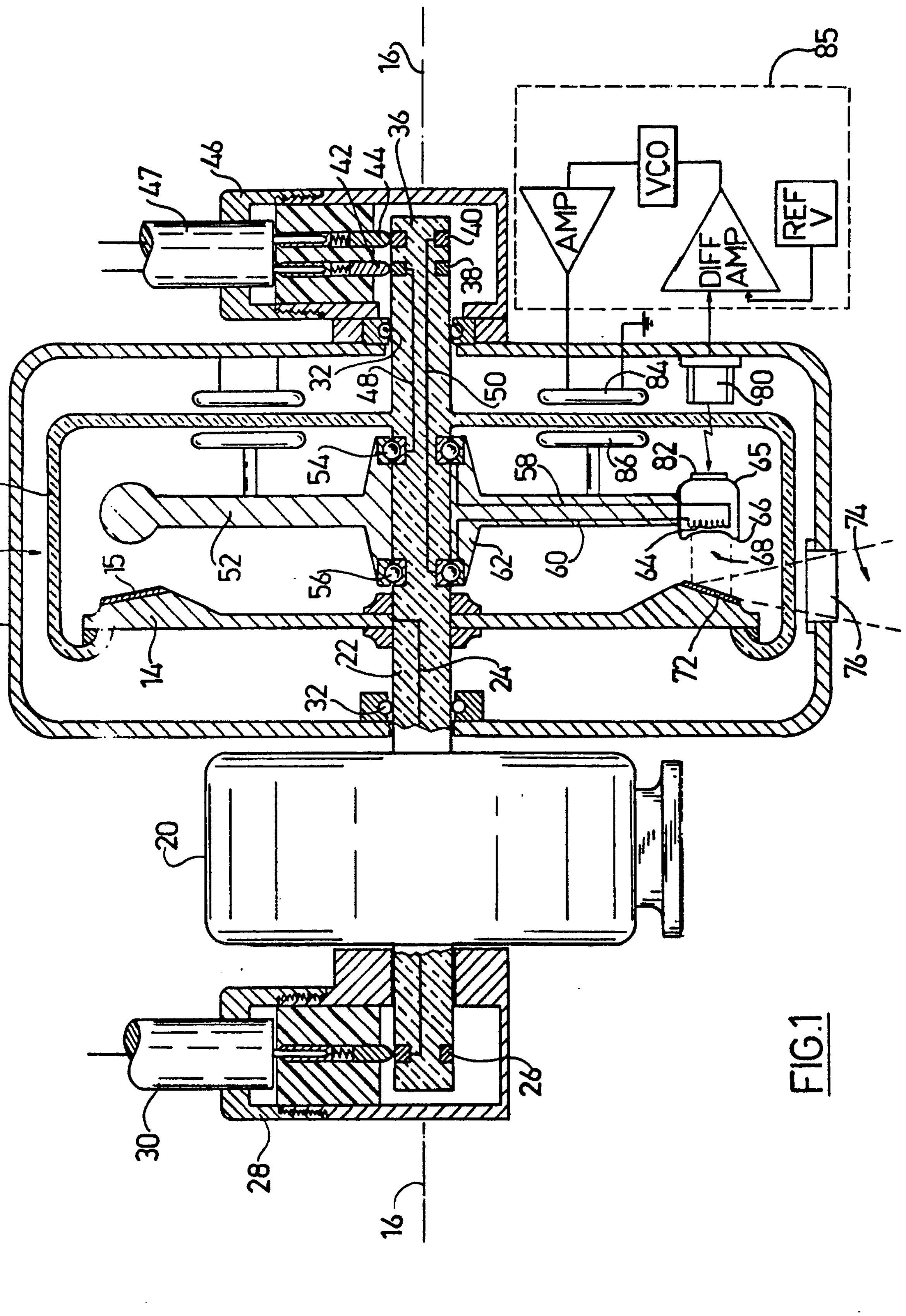

FIG.1

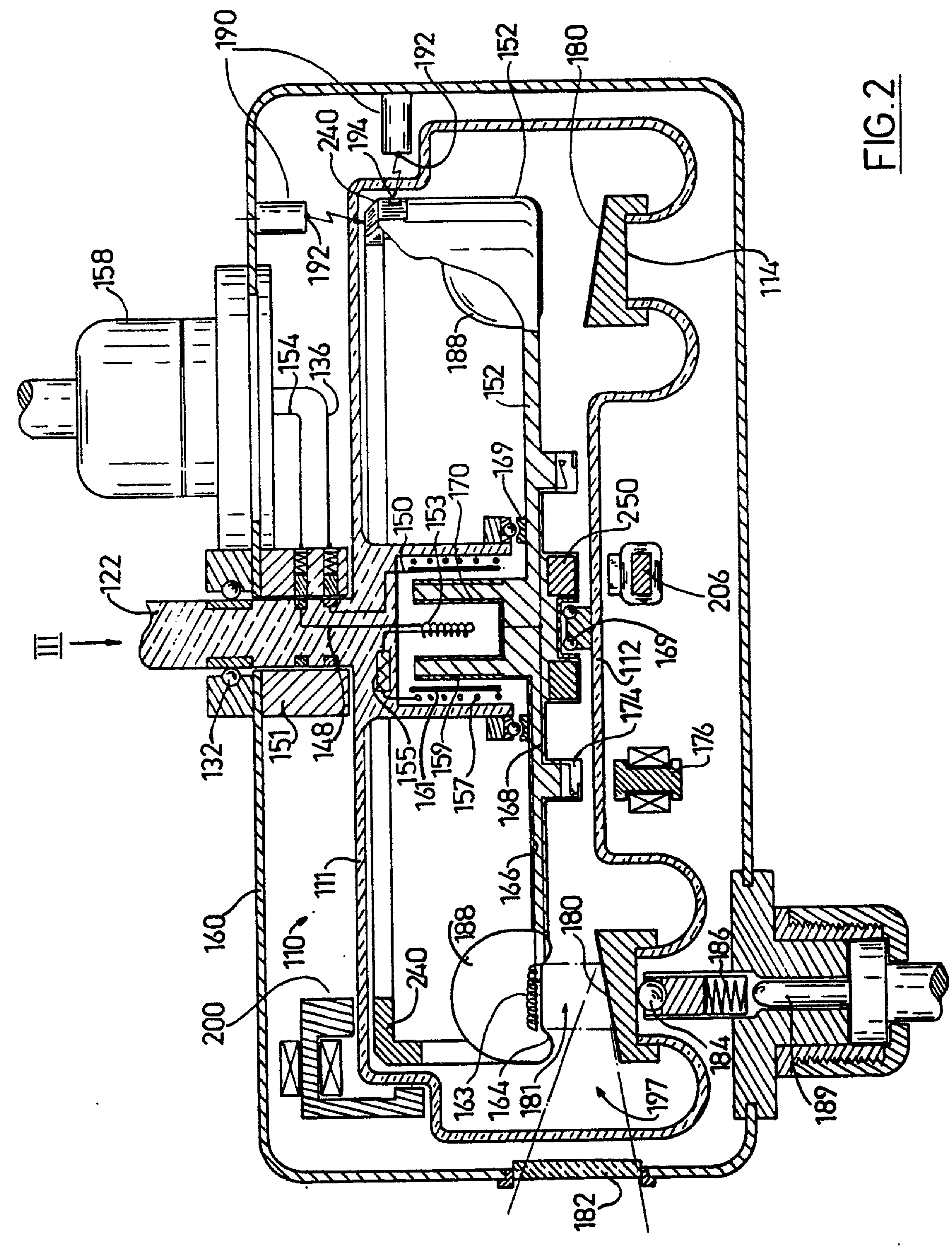

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FIG.2

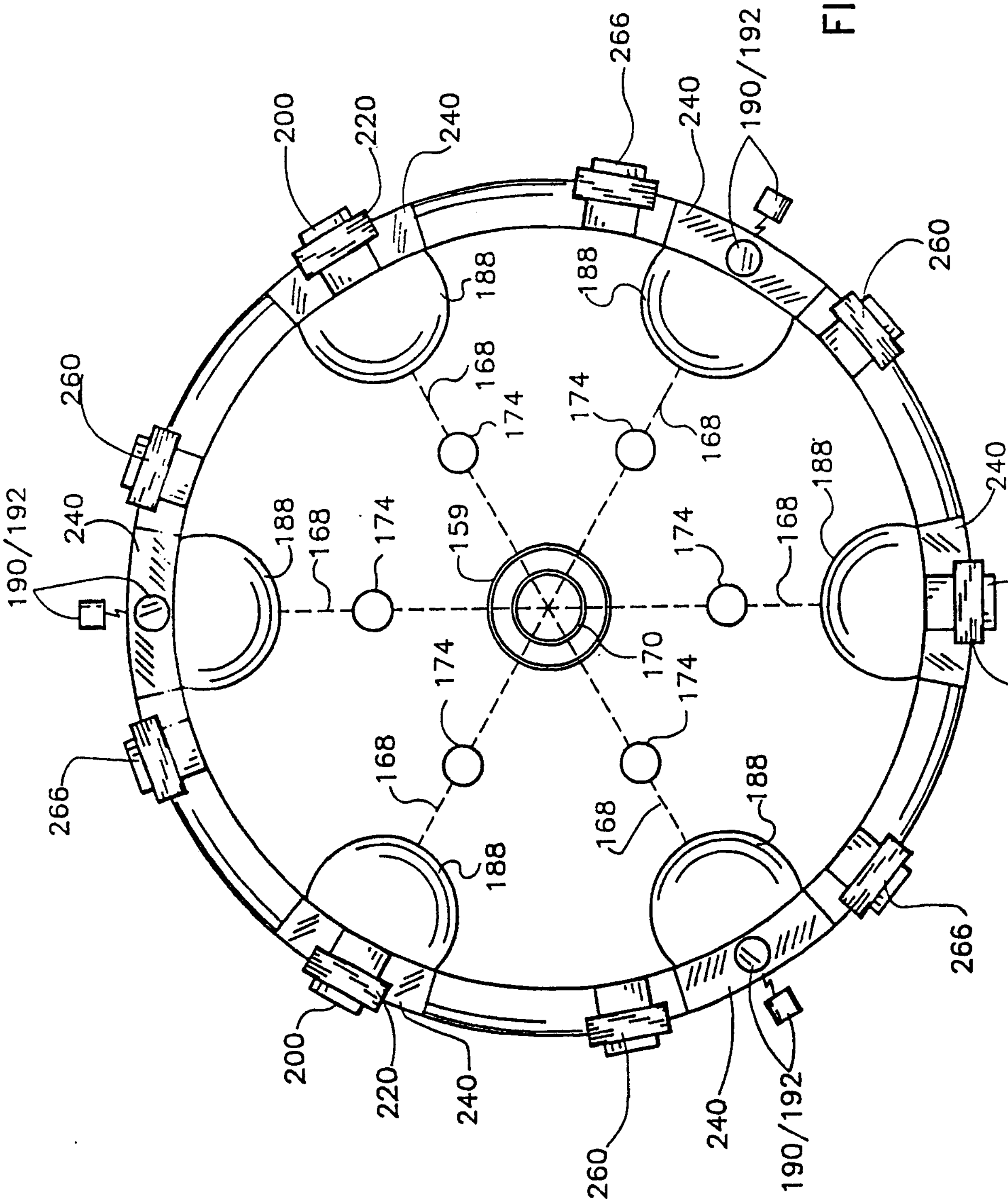
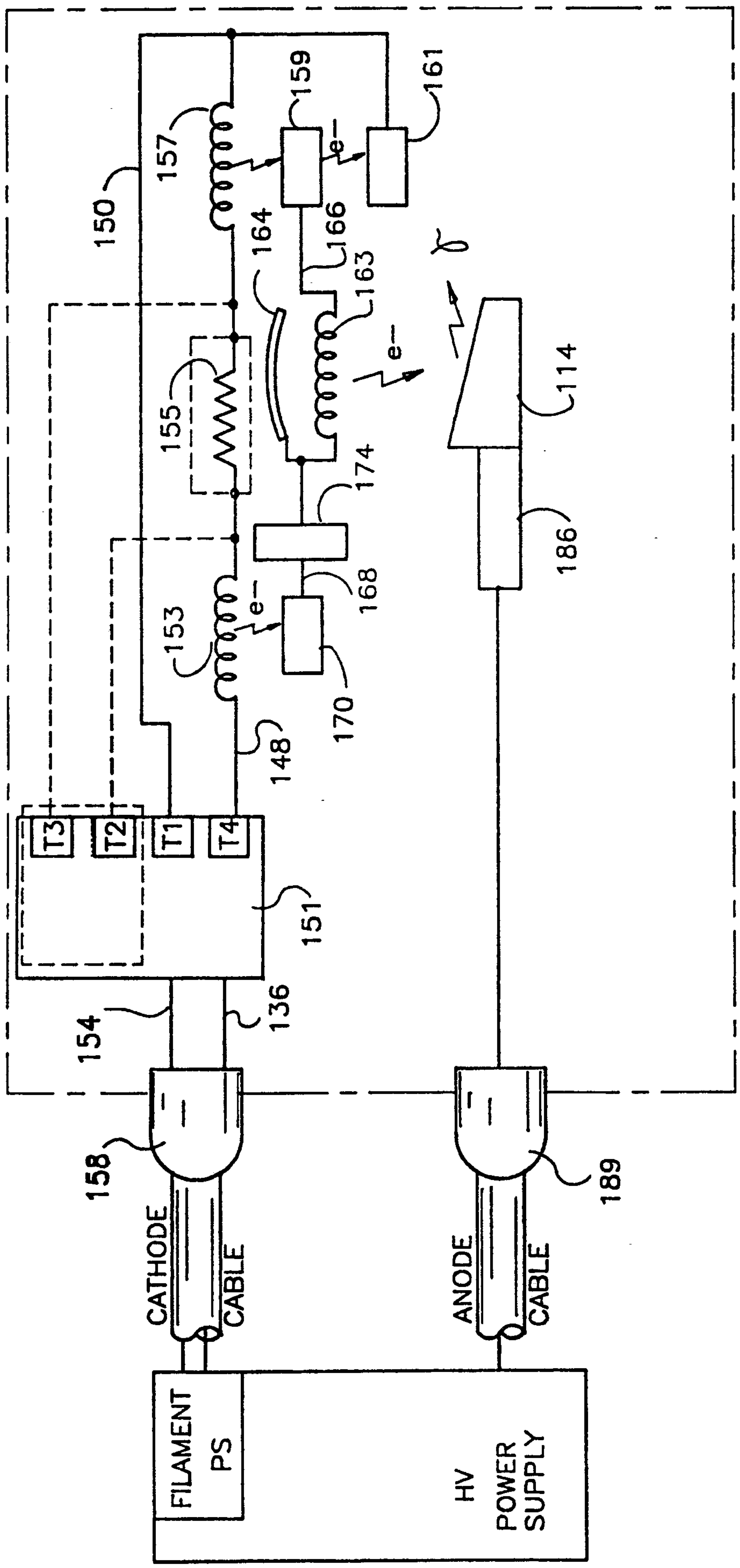


FIG.3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T3
T2
T1
T4
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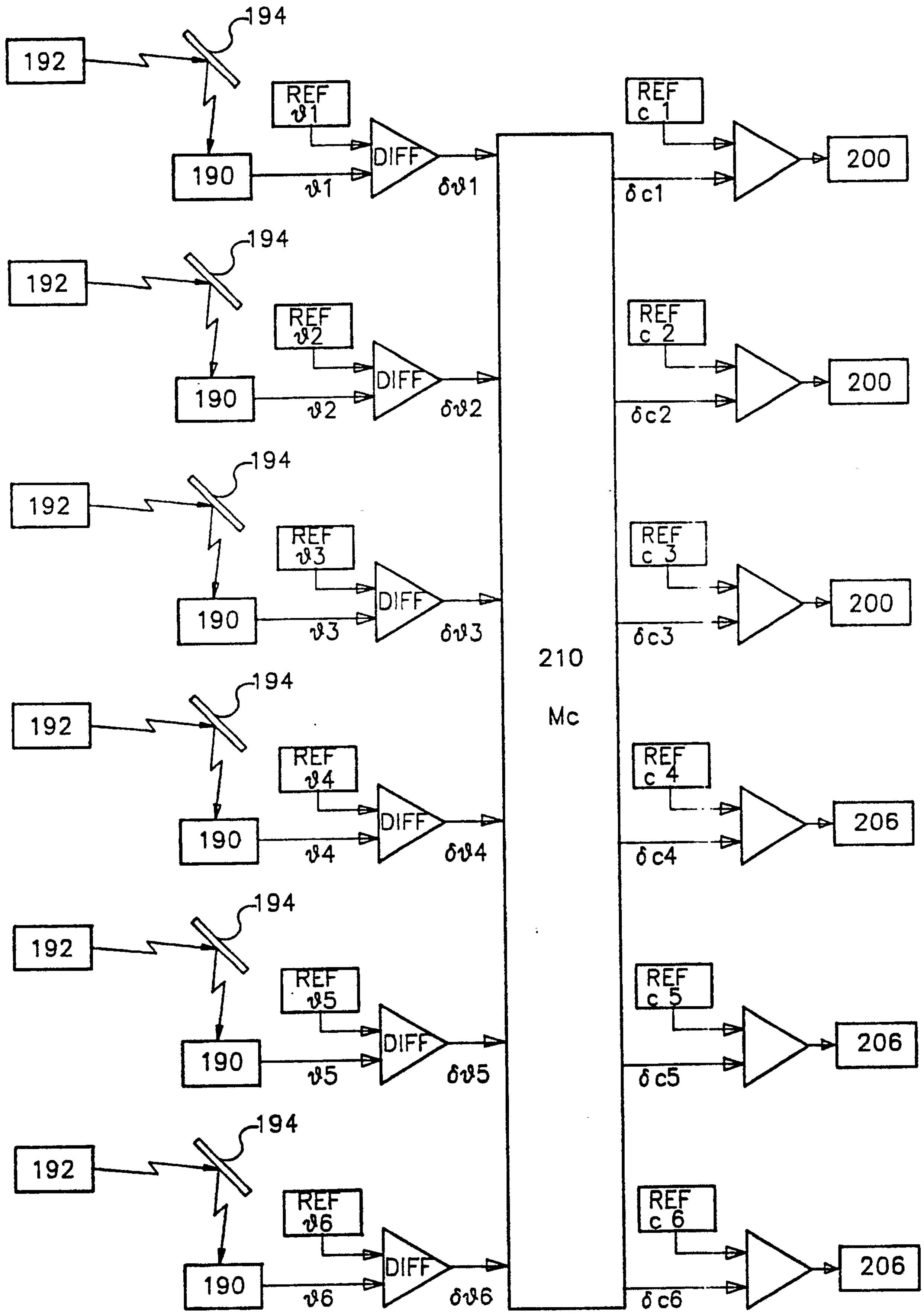
CATHODE
CABLE
ANODE
CABLE
FILAMENT
PS
HV
POWER
SUPPLY

FIG.4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δc6

FIG.5

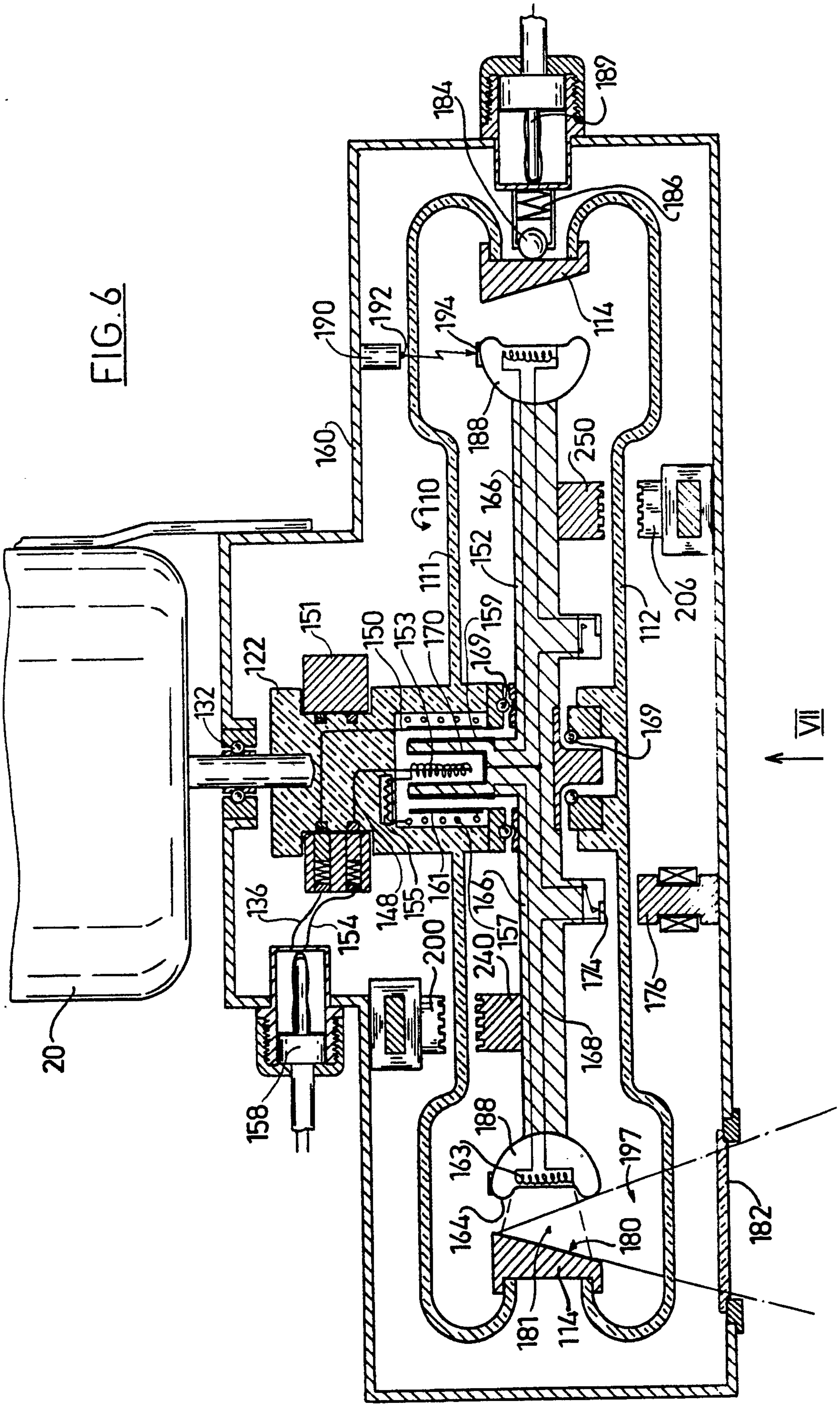
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FIG. 6

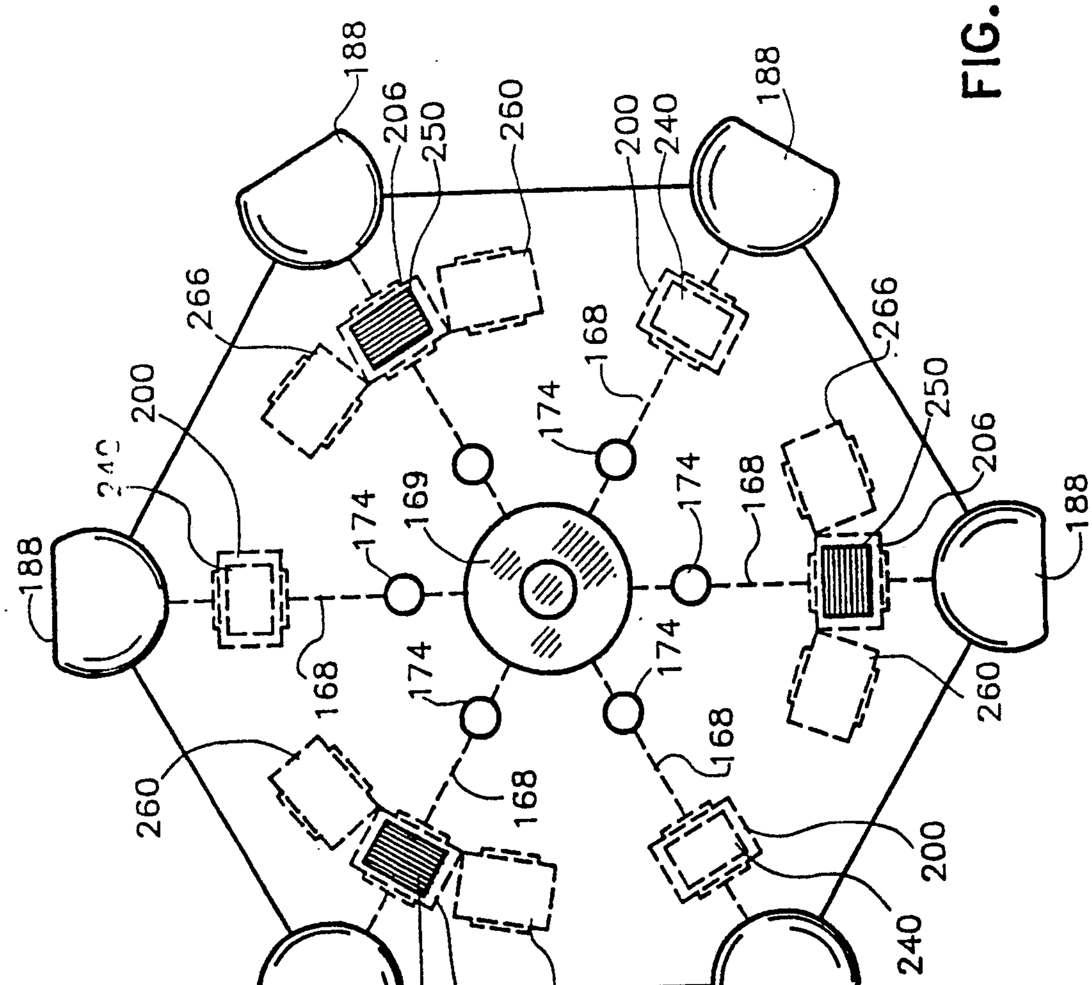
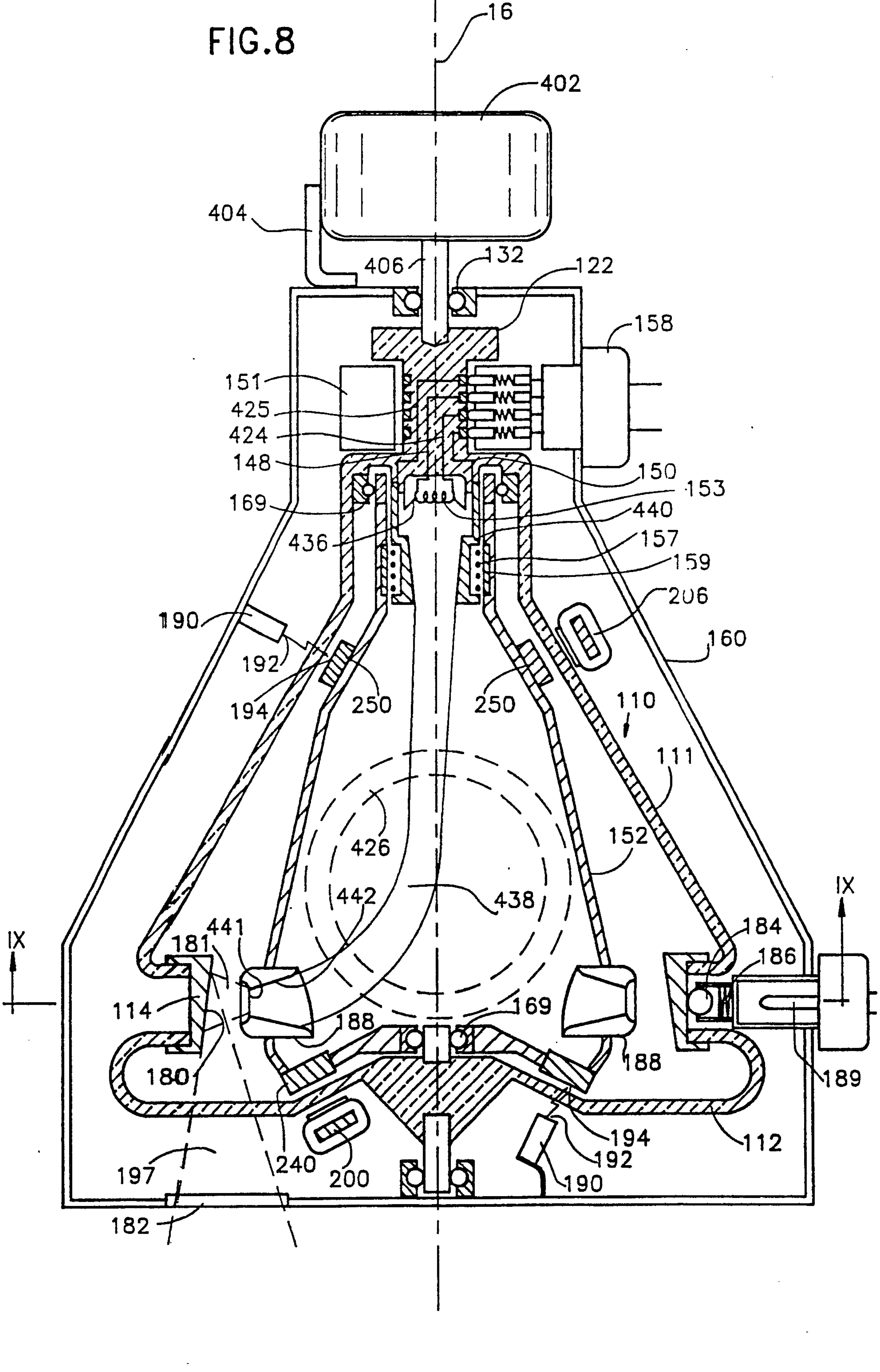


FIG.7

FIG.8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IX
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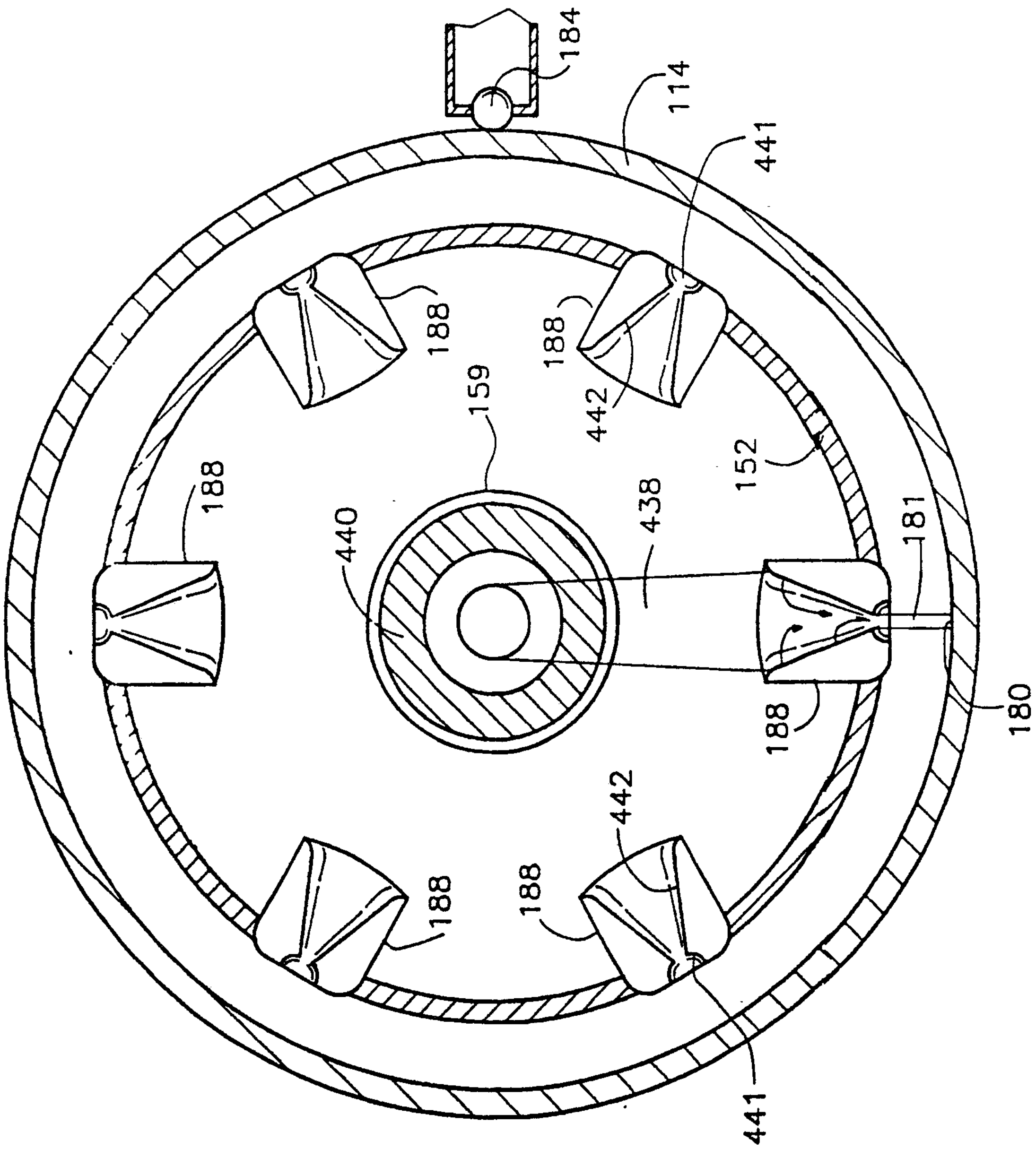
FIG.9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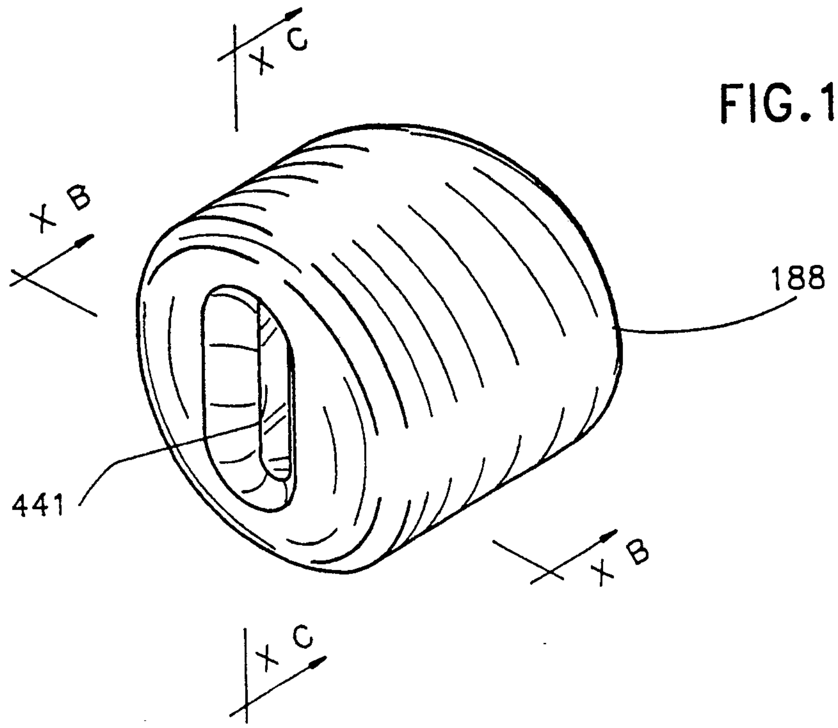

FIG.10A

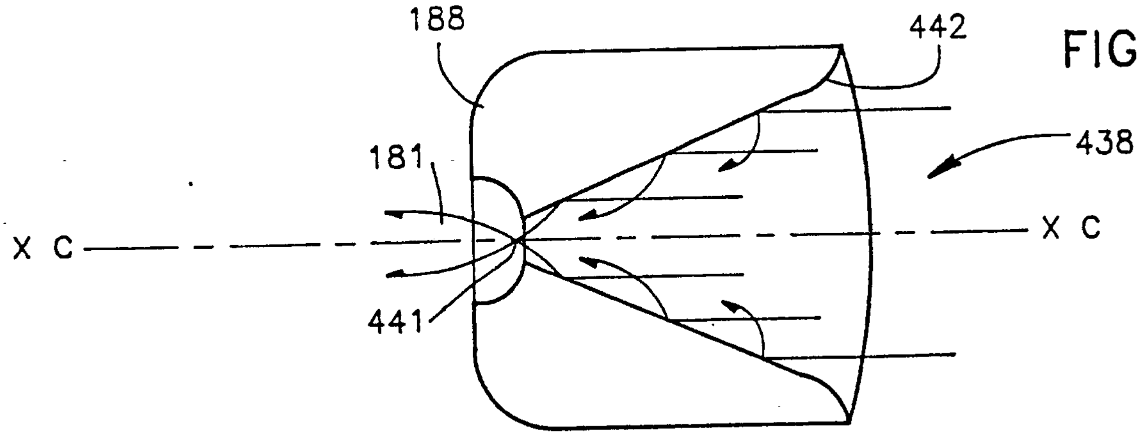

FIG.10B

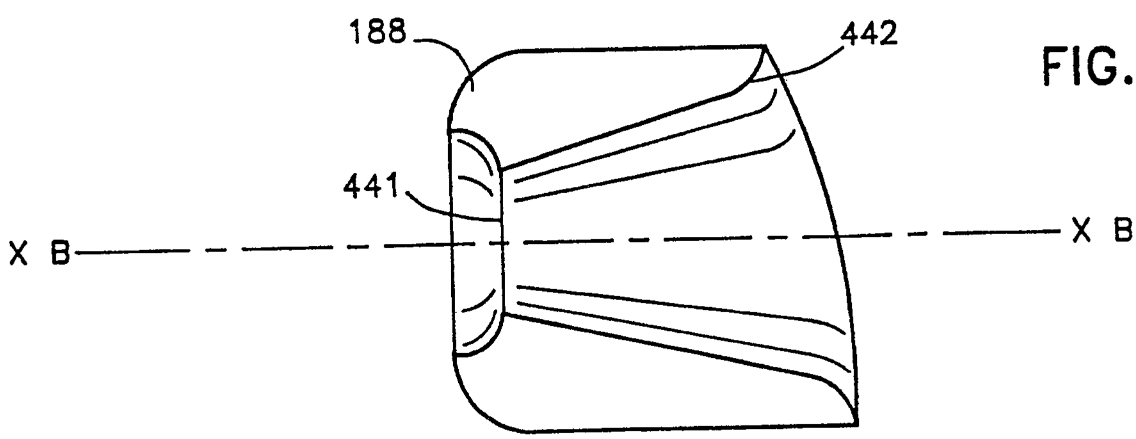

FIG.10C

FIG.11

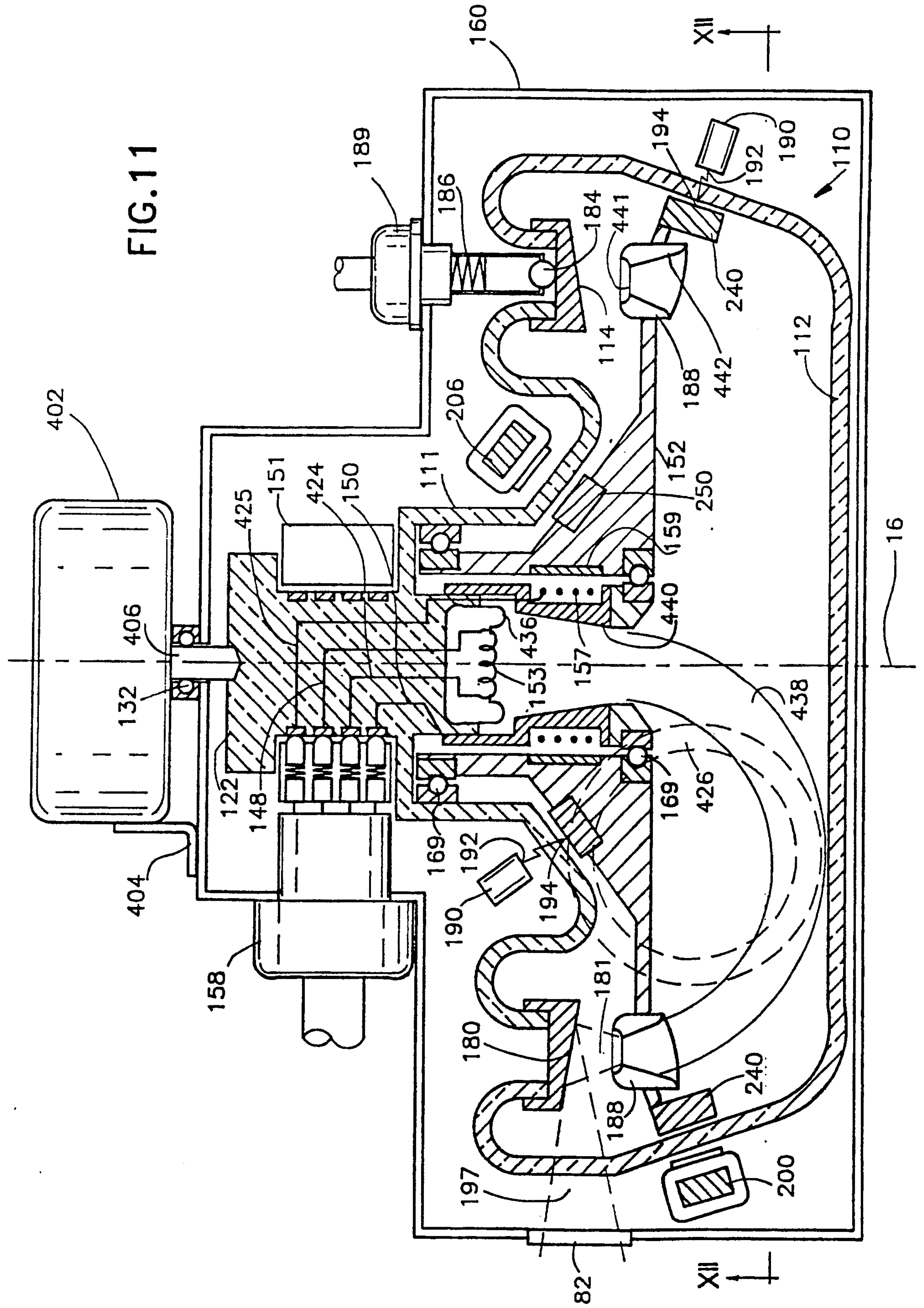
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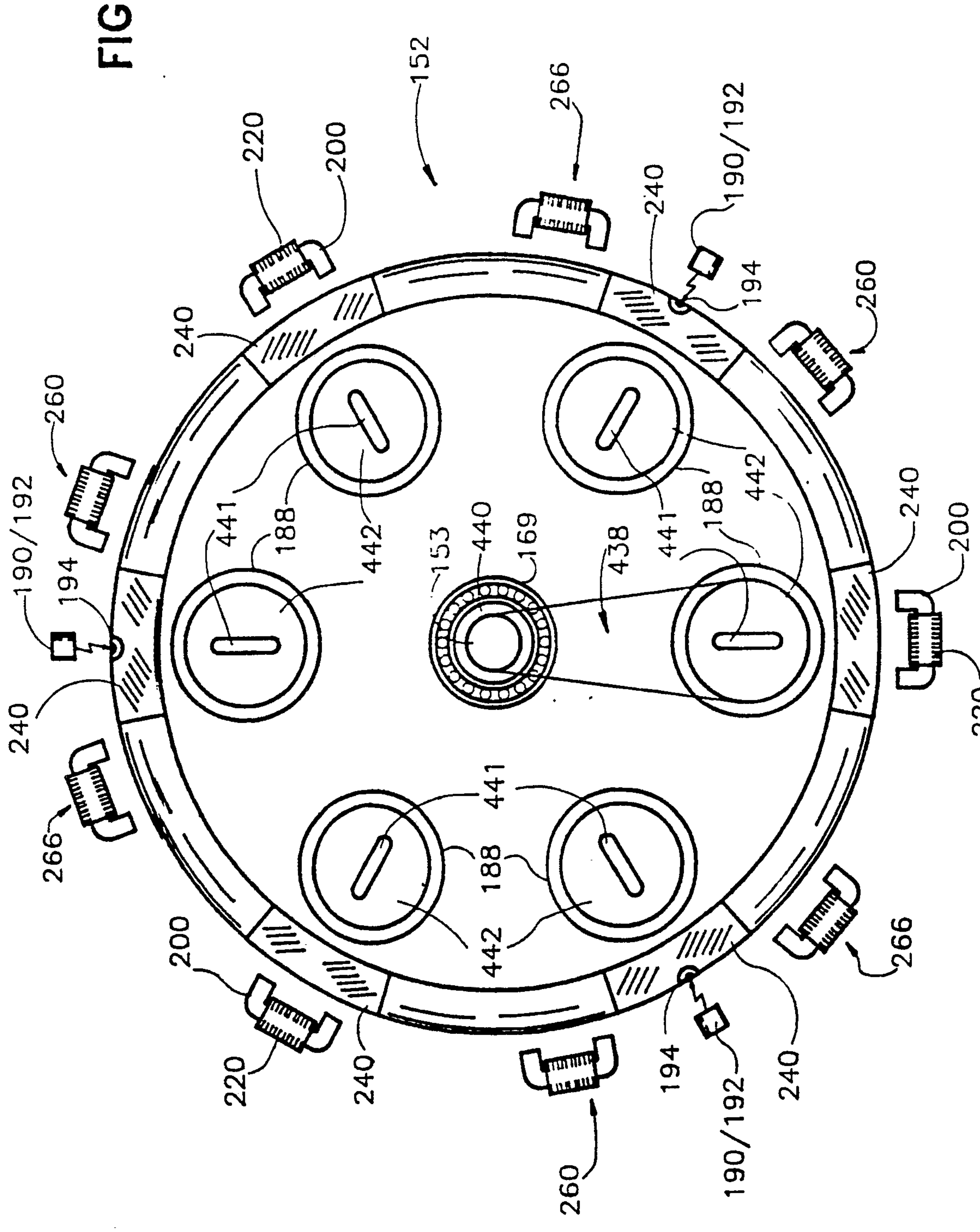
FIG.12



European Patent Office

EUROPEAN SEARCH REPORT

Application number

EP 90400022.1

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int Cl 5)
X	US - A - 2 209 963 (DU MOND) * Fig. 1,5; page 1, lines 1-22; page 2, lines 11-68; claims 1-5 *	1	H 01 J 35/10 H 01 J 35/24 H 01 J 35/16
A		2,6	
A	US - A - 4 675 891 (PLESSIS) * Fig. 2,3; claims *	1,3,4,7	
A	EP - A2 - 0 187 020 (VARIAN) * Fig. 1,5; page 3, line 35 - page 4, line 17; page 6, line 22 - page 7, line 7 *	10,11	
A	FR - A1 - 2 599 555 (THOMSON-CGR)		
P,X	EP - A2 - 0 330 336 (EVARIAN) * Fig. 4; column 6, lines 21-50; claims *	1	

TECHNICAL FIELDS SEARCHED (Int Cl 5)

H 01 J 35/00
H 01 J 1/00
H 05 G 1/00

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
VIENNA	28-03-1990	BRUNNER

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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