United States Patent [19]

Braun et al.

[11] 3,867,637

[45] Feb. 18, 1975

[54] EXTENDED MONOCHROMATIC X-RAY SOURCE

[75] Inventors: **Martin Braun; Howard D. Doolittle,** both of Stamford, Conn.; **Harrison H. Barrett,** Lexington, Mass.; **Jay P. Sage,** Newton Centre, Mass.; **David T. Wilson,** Billerica, Mass.

[73] Assignee: **Raytheon Company,** Lexington, Mass.

[22] Filed: **Sept. 4, 1973**

[21] Appl. No.: **393,772**

[52] **U.S. Cl.** **250/503,** 250/460, 250/505

[51] **Int. Cl.** **H01j 35/16**

[58] **Field of Search** 250/460, 419, 363, 503, 250/510, 272; 313/330

[56] **References Cited**

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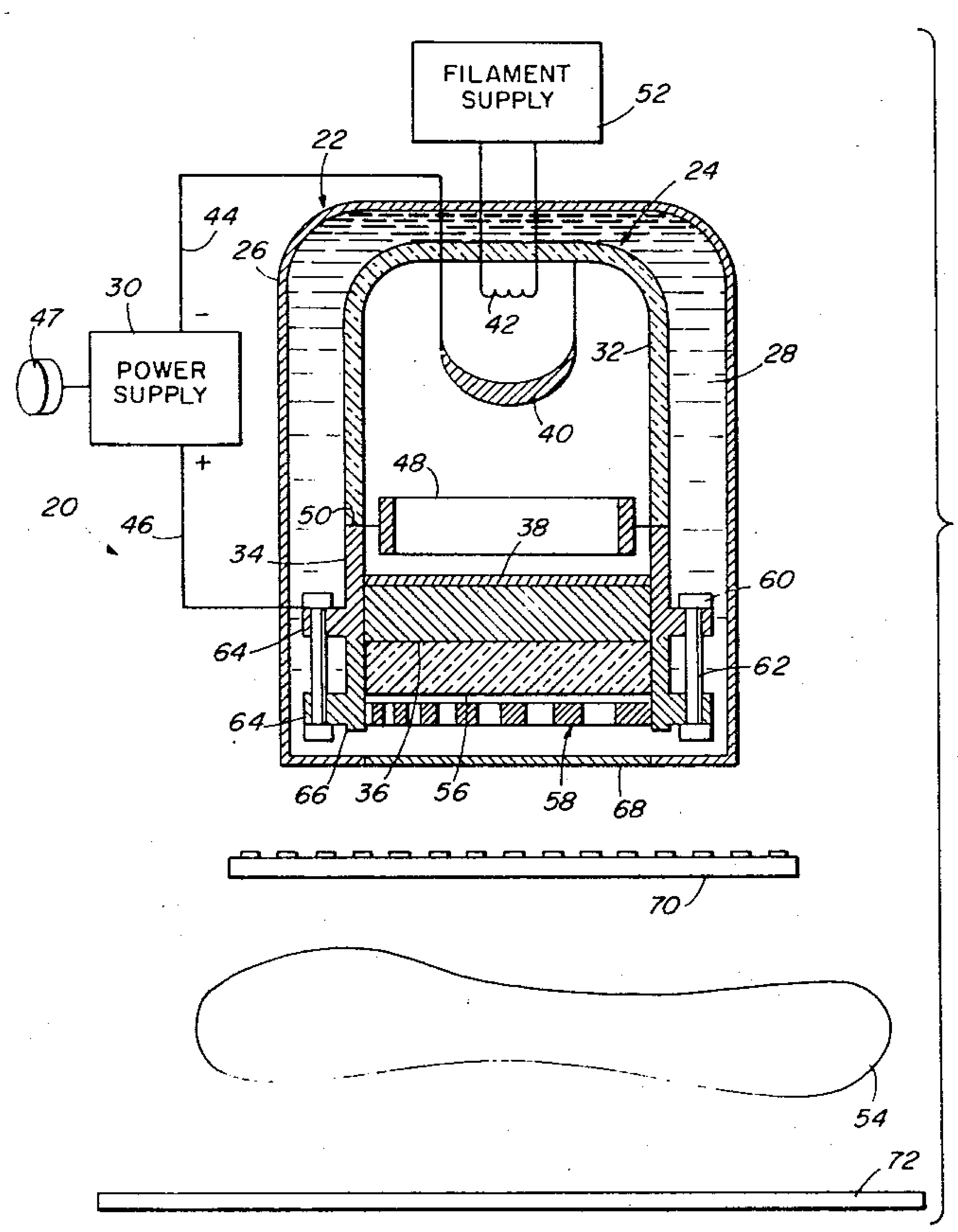
Primary Examiner—James W. Lawrence
Assistant Examiner—B. C. Anderson
Attorney, Agent, or Firm—Milton D. Bartlett; J. D. Pannone; D. M. Warren

[57] **ABSTRACT**

An extended radiating aperture for X-rays is provided by means of a stationary target of a heavy metal positioned for uniform illumination by high speed electrons emanating from a cathode and accelerating through a difference of potential between the cathode and the target. The target is in the form of a relatively thin film which can be deposited on a substrate transparent to X-radiation. A layer of fluorescent material is placed adjacent the substrate on the opposite side thereof from the target so that X-rays generated within the target material pass through the target material and impinge on the fluorescent layer. The fluorescent material enhances the monochromaticity of the X-ray spectrum by emitting fluorescent X-radiation while substantially absorbing incident X-radiation having energies above the fluorescent radiation spectrum. A zone plate is positioned adjacent the fluorescent layer to spatially modulate the radiation of the radiating aperture to provide this radiation with a spatial frequency spectrum suitable for obtaining high resolution roentgenograms. The zone plate provides a coding on the roentgenogram which is then decoded by an optical processor to form a visible image of an object being X-rayed. Alternative embodiments of the invention include the use of an inclined transmissive target, a transmissive target having serrations, and the use of a moire pattern mask between the target and the fluorescent material to augment fluorescent radiation from the target and to inhibit the passage of X-radiation normal to the layer of fluorescent material.

15 Claims, 10 Drawing Figures



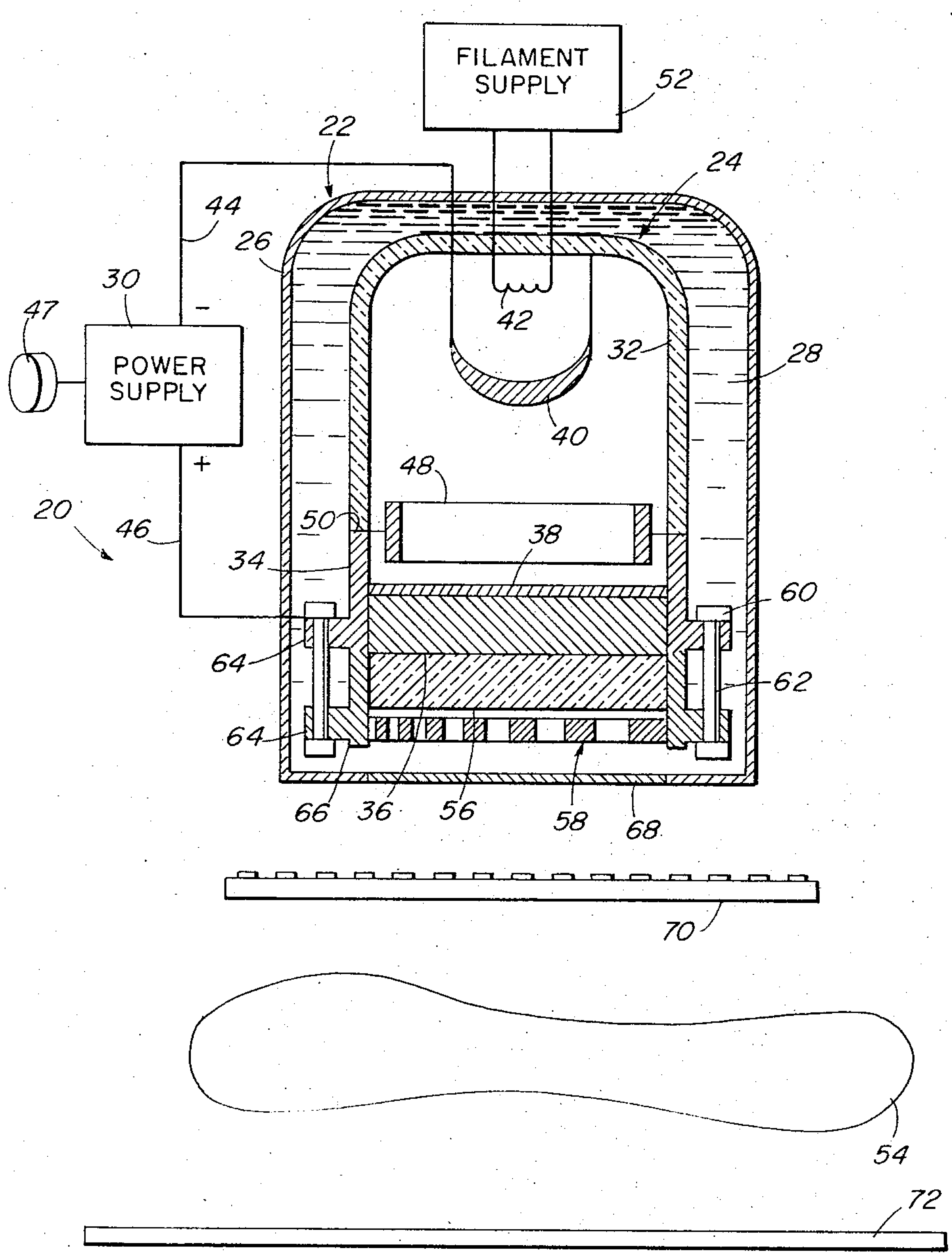

FILAMENT SUPPLY
POWER SUPPLY
52
22
24
44
26
30
47
42
32
28
40
48
20
46
50
38
34
60
64
62
64
66
36
56
58
68
70
54
72

FIG. 1

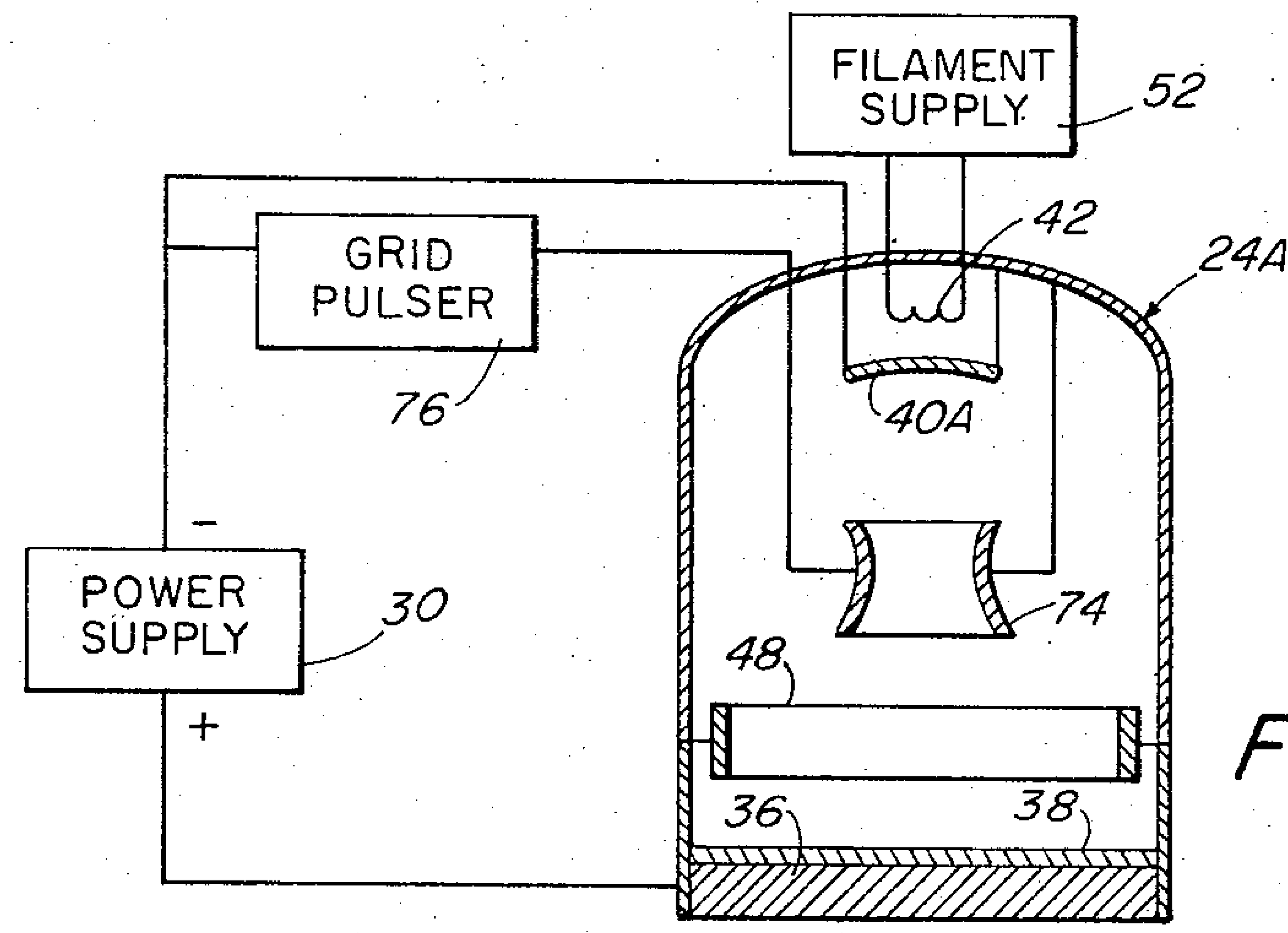

FILAMENT SUPPLY
GRID PULSER
POWER SUPPLY
52
42
24A
76
40A
74
30
48
36
38

FIG. 2

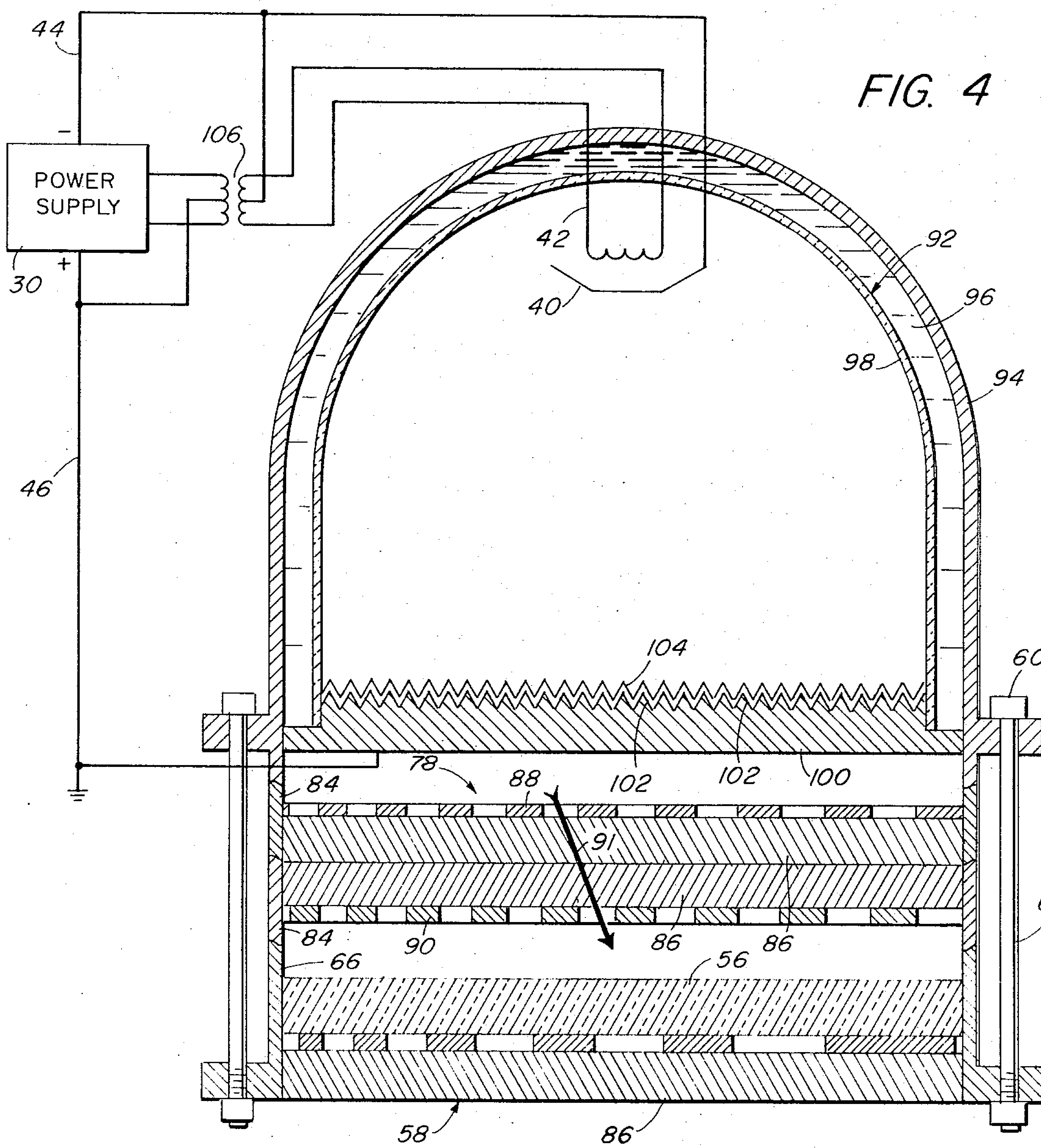

POWER
SUPPLY
30
44
46
106
42
40
92
96
98
94
104
60
64
78
84
88
91
102
100
62
90
86
66
56
58

FIG. 4

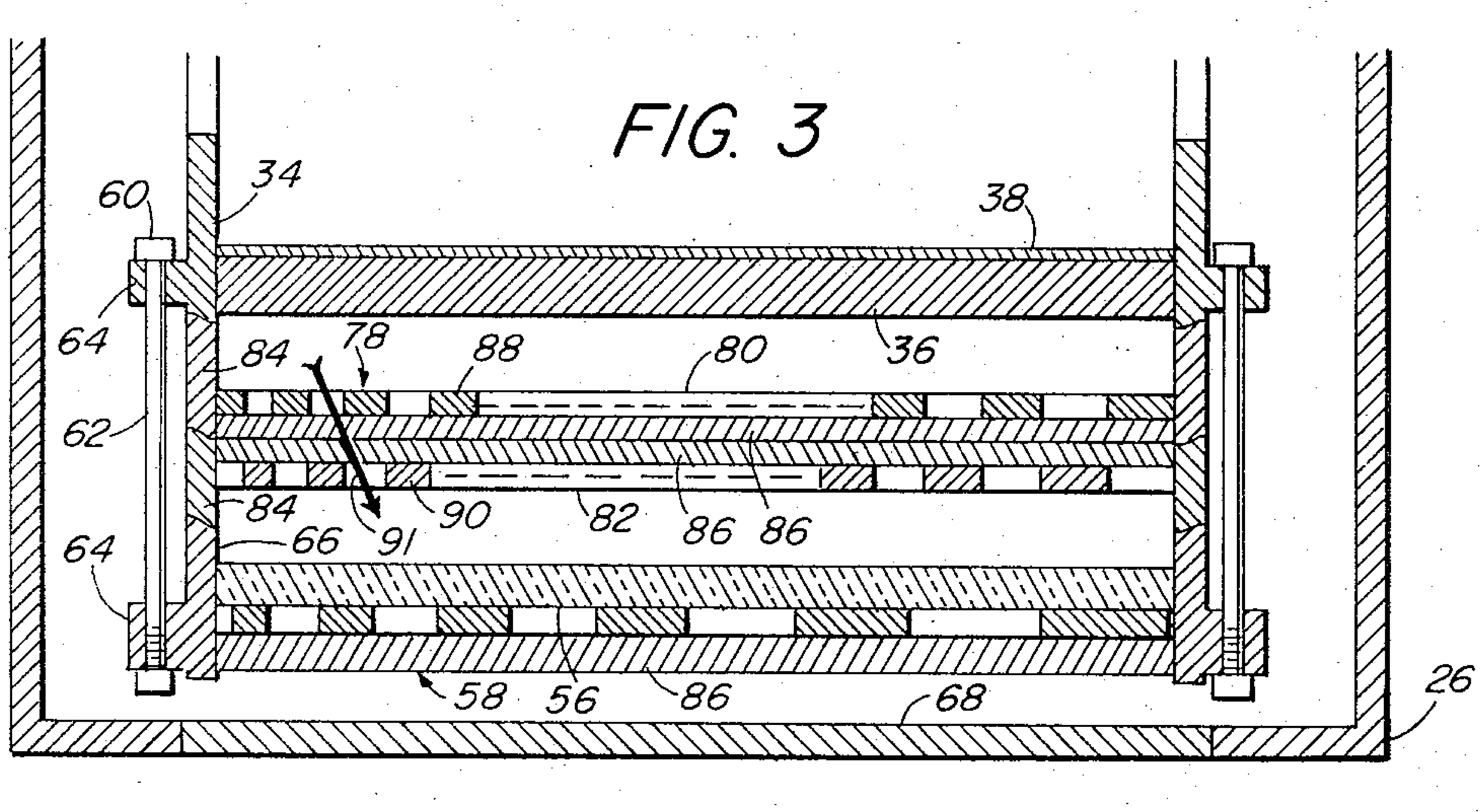

34
38
60
64
78
84
88
80
36
62
90
82
86
91
66
58
56
68
26

FIG. 3

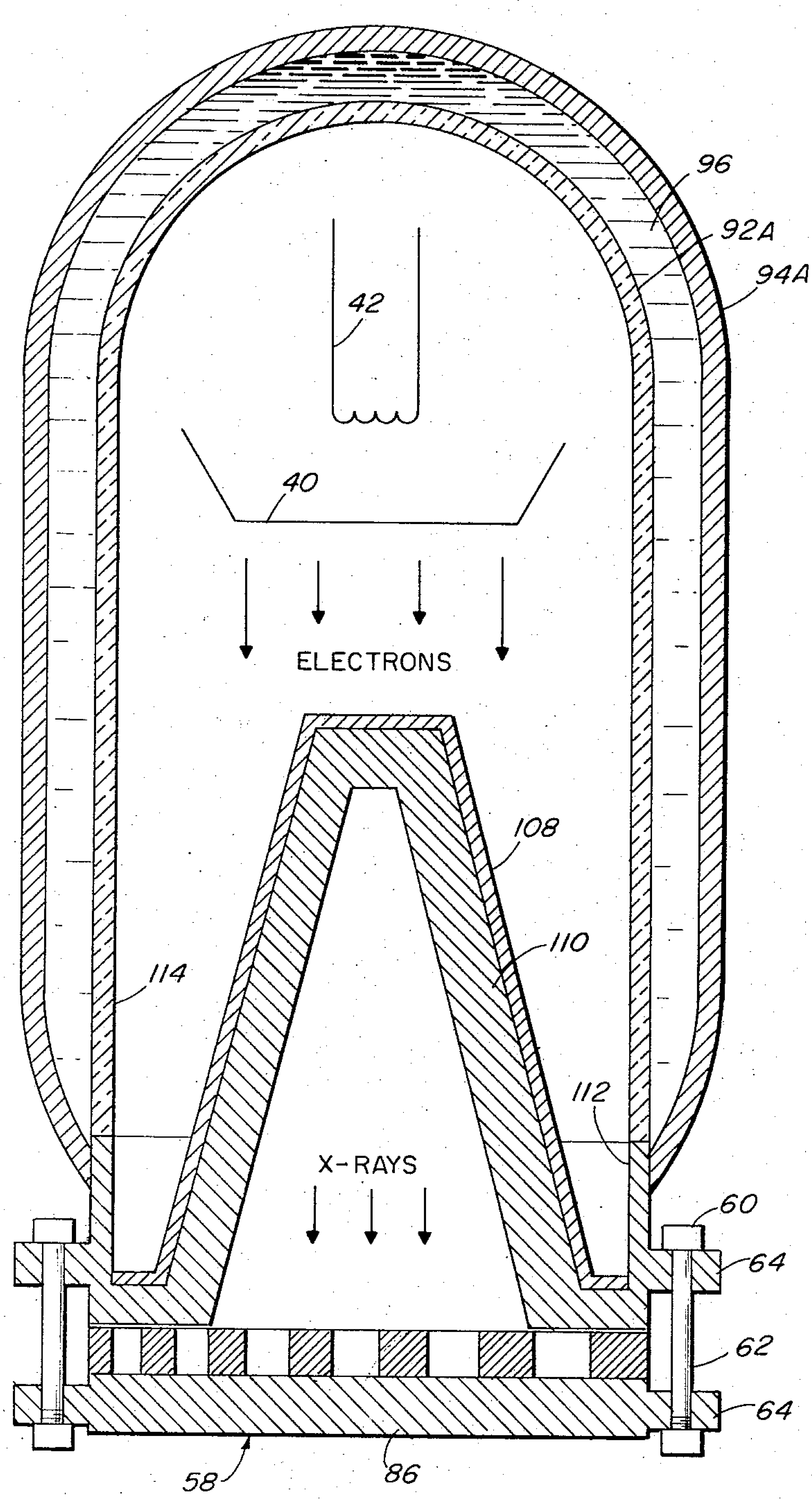

96
92A
94A
42
40
ELECTRONS
108
110
114
112
X-RAYS
60
64
62
64
58
86

FIG. 5

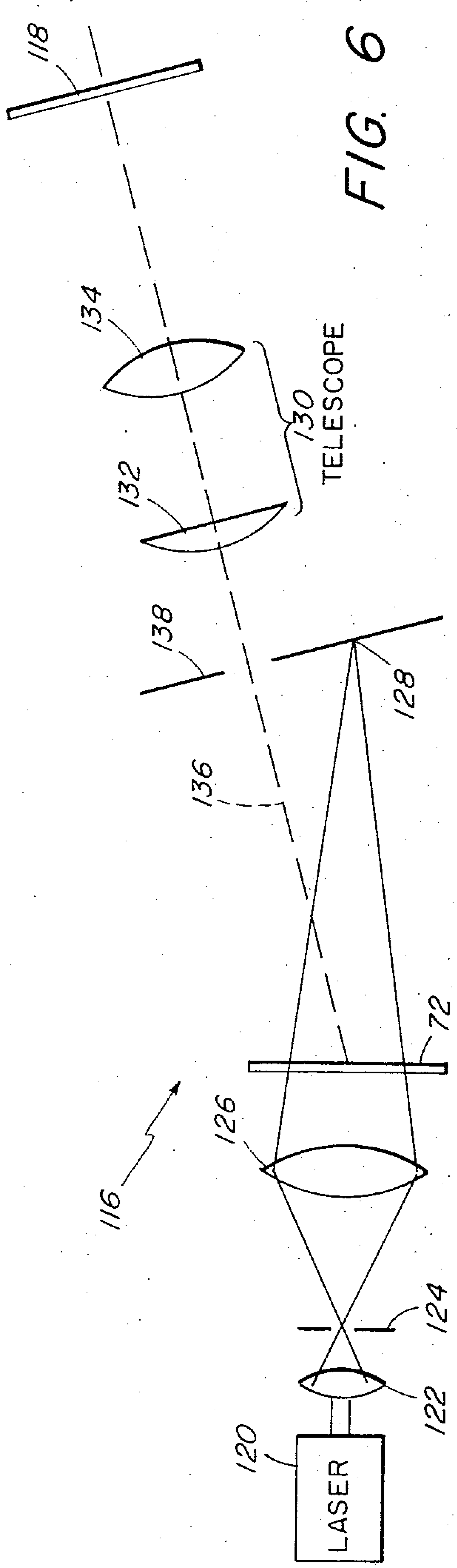

LASER
TELESCOPE
120
122
124
126
116
72
128
136
138
132
130
134
118

FIG. 6

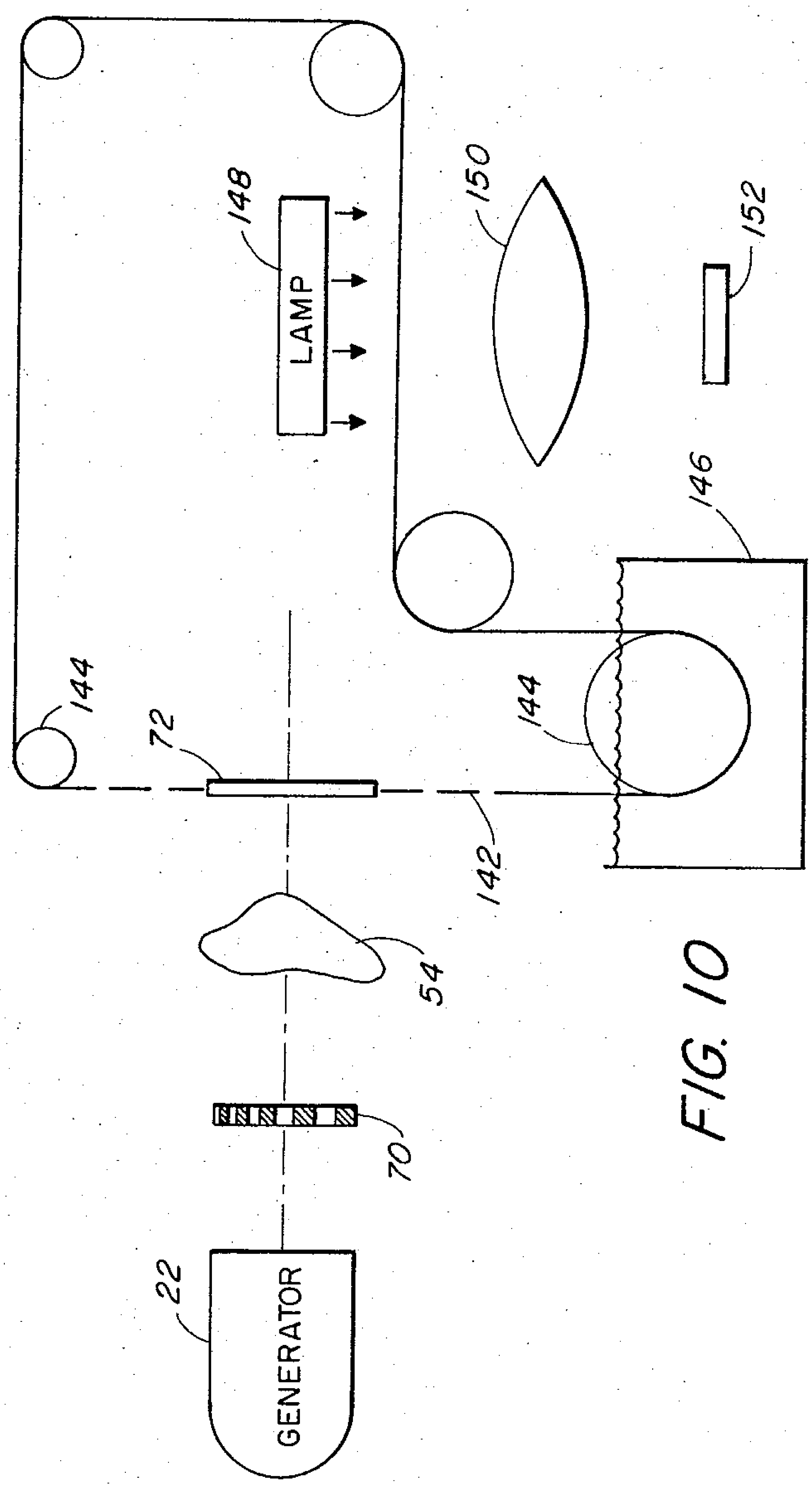

LAMP
GENERATOR
148
150
152
146
144
144
72
142
54
70
22

FIG. 10

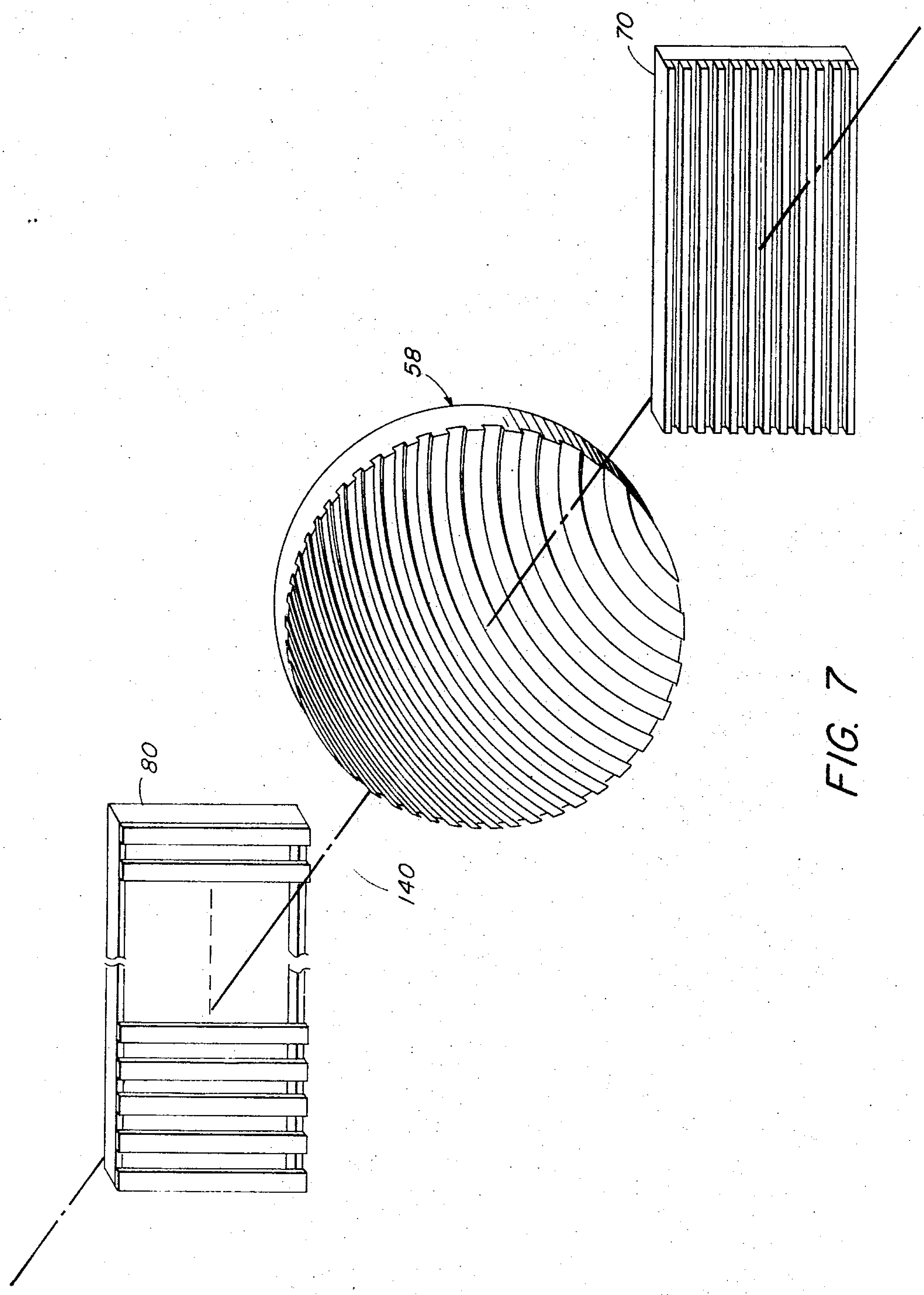


FIG. 7

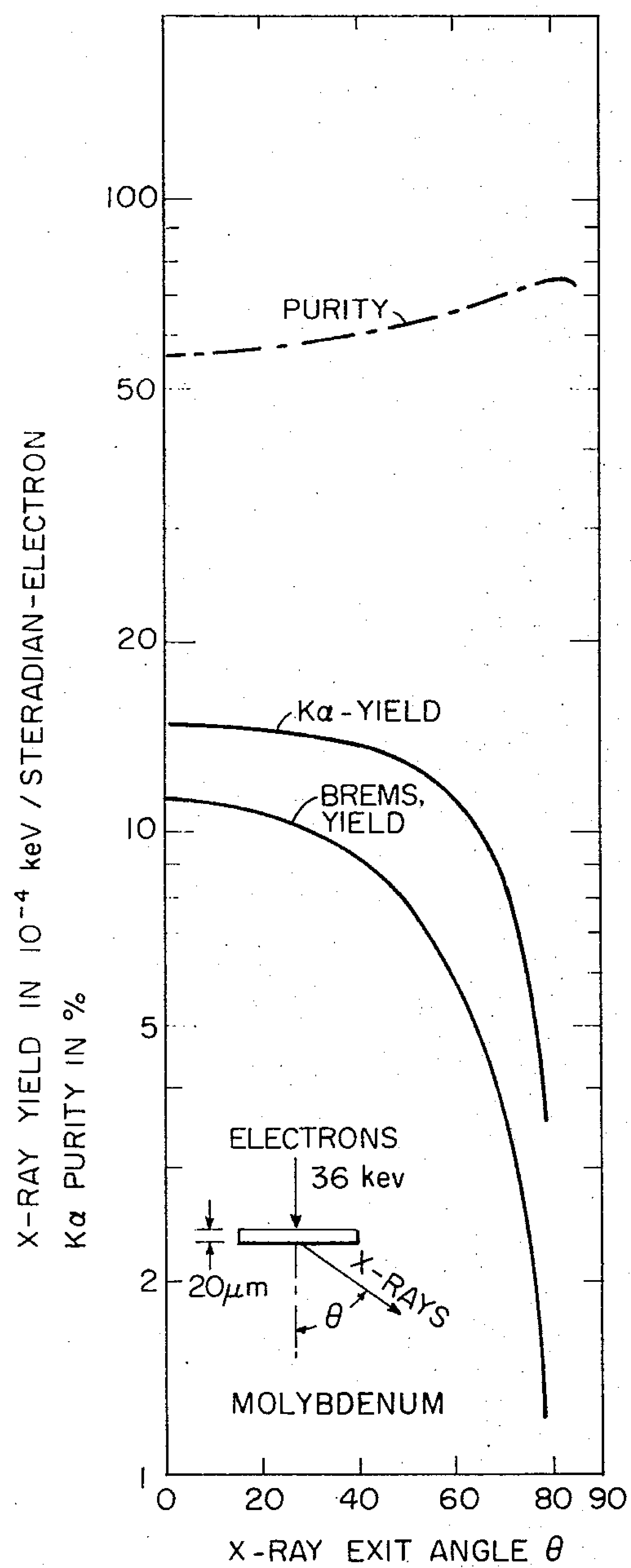

X-RAY YIELD IN 10^{-4} keV / STERADIAN-ELECTRON
Kα PURITY IN %
100
50
20
10
5
2
1
PURITY
Kα-YIELD
BREMS, YIELD
ELECTRONS
36 kev
20μm
X-RAYS
θ
MOLYBDENUM
0
20
40
60
80
90
X-RAY EXIT ANGLE θ

FIG. 8

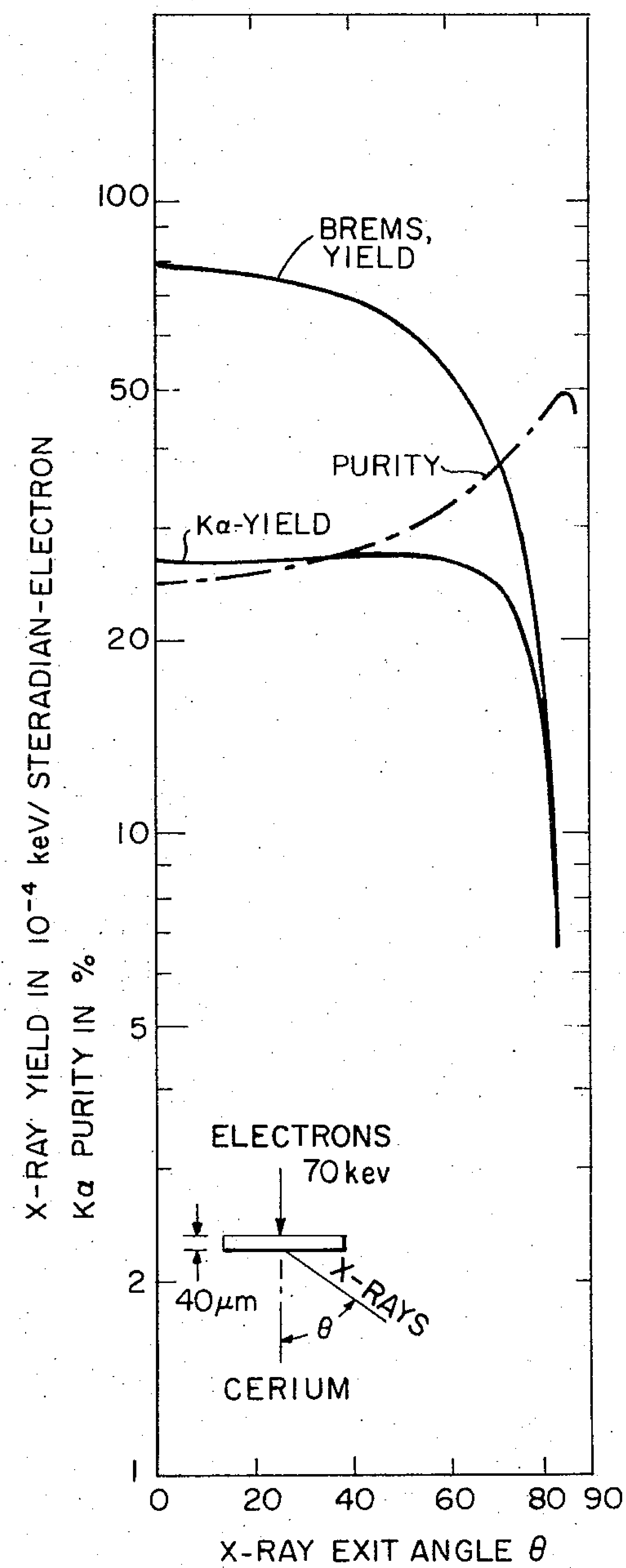

X-RAY YIELD IN 10^{-4} keV/ STERADIAN-ELECTRON
Kα PURITY IN %
100
50
20
10
5
2
1
BREMS, YIELD
PURITY
Kα-YIELD
ELECTRONS
70 kev
40μm
X-RAYS
θ
CERIUM
0
20
40
60
80
90
X-RAY EXIT ANGLE θ

FIG. 9

EXTENDED MONOCHROMATIC X-RAY SOURCE

BACKGROUND OF THE INVENTION

Roentgenography frequently requires that intense X-radiation be provided over a relatively short interval of time, for example, one-tenth second or less in the case of an angiogram to prevent blurring of the image due to motion of the blood vessels of a human subject. For radiograms of the human skeleton, longer exposure times can be accommodated so long as the patient can remain stationary. Shorter exposure times require the use of higher intensity radiation for good quality images on the photographic plate since the total incident energy required to produce the image on the photographic plate is approximately the same for both short and long exposure times. A problem arises in that there is a limited intensity of radiation that can be provided by the typical rotating anode target of an X-ray tube because of overheating of the target at the point of impact of an electron beam upon the target. This problem is further intensified by the fact that high resolution radiography requires that the target emit the X-rays from a relatively small spot, typically less than ten square millimeters, thereby increasing the temperature of the target.

It is known that a monochromatic source of radiation should produce a sharper photographic image than a broad spectrum source. This would be most useful, for example, in the case of angiography wherein a dye, opaque to a specific frequency or band of frequencies, is injected into or ingested by a human subject. The dye absorbs the radiation to which it is opaque thereby creating sharply defined shadows on an X-ray plate to provide a high resolution image of minute details such as blood vessels in the human subject. A problem arises in that a broad spectrum source of X-radiation illuminates the dyed regions of the human subject with radiation lying both within and without the absorption band of the dye thereby degrading the photographic image.

SUMMARY OF THE INVENTION

The aforementioned problems are overcome and other features are provided by an X-ray source and system for using the source in accordance with the invention wherein there is provided an X-ray tube comprising a source of high energy electrons and a relatively thin transmissive target illuminated by the electrons and emitting X-rays on the side of the target opposite the side which is illuminated by the electrons. In one embodiment of the invention, a side of the target is inclined relative to an exit window of the X-ray tube to augment the percentage of fluorescent X-rays which are generated by the target relative to the total spectrum of X-rays emitted by the target. This provides enhanced monochromaticity to the X-rays propagating through the window of the X-ray tube. In an alternative embodiment of the invention, enhanced monochromaticity is obtained by the use of a layer of fluorescent material positioned in front of the window of the X-ray tube for absorbing the incident or primary radiant energy of the X-rays and re-radiating energy at a fluorescent frequency. The fluorescent material, to be referred to hereinafter as the fluorescer, absorbs a large portion of the bremsstrahlung and fluorescent X-rays of the target so that the radiation emitted by the fluorescer is substantially monochromatic in that the major

portion thereof is the fluorescent X-radiation emitted by the fluorescer itself.

To provide a large spectral bandwidth to the spatial frequency characteristic of the radiation emitted by the fluorescer, a zone plate, such as that disclosed in U.S. Pat. No. 3,748,470 which issued on July 24, 1973 to Harrison H. Barrett having a chirpped checkerboard pattern or, alternatively, a zone plate in the form of an off-axis Fresnel pattern, is utilized to spatially modulate the emitted X-radiation. The X-ray tube with the zone plate attached thereto is then positioned for directing the X-radiation towards a patient behind which is a standard photographic plate commonly used in roentgenography. A coded photograph of the internal structure of the subject is obtained in view of the coding provided by the zone plate. The photograph on the X-ray plate is first decoded in order to provide an intelligible image which may be viewed by a radiologist for observing the internal structure of the subject. In the case of the off-axis Fresnel pattern zone plate, the decoding of the photograph, or reconstruction of the image, is readily accomplished by a relatively simple optical system employing an off-axis iris and telescope. A random pattern zone plate may also be used.

The invention further contemplates, in one embodiment thereof, the use of a pair of masks spaced apart from each other and placed between the target and the fluorescer to provide a radiation pattern in the form of a moire pattern wherein the primary radiation from the target is stopped from propagating in the forward direction but is permitted to propagate in directions slightly angled from the forward direction, this providing illumination of the fluorescer while inhibiting the passage of the primary radiation through the fluorescer towards the subject resulting in improved monochromaticity to the radiation emitted from the fluorescer. There is also disclosed a half-tone screen which is placed between the zone plate and the subject for spatially modulating the subject as viewed by the incident radiation, thereby making the subject appear as a high spatial frequency subject which is more accurately photographed in this zone plate system.

BRIEF DESCRIPTION OF THE DRAWINGS

The aforementioned aspects and other advantages of the invention are explained in the following description taken in connection with the accompanying drawings wherein:

FIG. 1 shows an X-ray tube having a fluorescer and zone plate in accordance with the invention;

FIG. 2 is an alternative embodiment of the X-ray tube of FIG. 1 employing a non-contacting grid structure for modulating the electron beam;

FIG. 3 shows the placement of a moire pattern mask assembly between the target and fluorescer of the tube of FIG. 1;

FIG. 4 shows an embodiment of the invention in which a serrated target has surfaces inclined relative to the window of the tube of FIG. 1, the figure further showing the mounting of the moire mask assembly and zone plate external to an oil-filled housing enclosing the tube;

FIG. 5 shows an alternative embodiment of the invention in which the target is conically shaped to provide an inclined surface;

FIG. 6 shows an optical system utilized in reconstructing an image from a coded photograph resulting from the coding by the zone plate;

FIG. 7 shows the arrangement of the mask assembly, the zone plate and the screen of FIGS. 1 and 3;

FIGS. 8 and 9 show spectra of molybdenum and cerium fluorescers for FIG. 1; and

FIG. 10 shows means for reducing the size of a photograph for FIGS. 1 and 6.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1 there is seen a system 20 which, in accordance with the invention, includes a generator 22 of X-rays. The generator 22 comprises an X-ray tube 24 which is enclosed by a housing 26 and immersed in oil 28 which is enclosed by the housing 26 and serves as insulation from the high voltage electric power which is provided by a power supply 30. The X-ray tube 24 comprises a glass envelope 32 which is sealed to a metallic base 34 which is, in turn, joined to a substrate 36 for maintaining a vacuum-tight region within the X-ray tube 24. A target 38 in the form of a thin foil or film of a heavy element, such as tungsten or gold, is deposited on the substrate 36 within the evacuated region of the X-ray tube 24. While the substrate 36 is utilized for supporting the target 38, the invention contemplates other means of support such as a frame (not shown) attached to the periphery of the target 38 when the target 38 is in the form of a foil. The use of the substrate 36 is preferred as it helps cool the target 38. A cathode 40 is heated by a filament 42 and emits electrons which illuminate the target 38 under the influence of a difference of electric potential established between the cathode 40 and the target 38 by means of the power supply 30 connected thereto by wires 44 and 46. A knob 47 connects with the power supply 30 to adjust the voltage between the wires 44 and 46 for selecting the energy of the X-rays. A shield 48 is provided adjacent the seal 50 between the glass envelope 32 and the metallic base 34 to protect the seal 50 from electrons emitted from the cathode 40.

The substrate 36 is preferably constructed of a light metal such as aluminum or beryllium which is essentially transparent to X-rays emitted by the target 38 while being adequately rigid to retain the target 38 in position and to overcome the pressure of the atmosphere acting against the vacuum within the X-ray tube 24. The filament 42 is energized with electric current from a filament supply 52, the filament 42 being energized prior to the operation of the generator 22 for heating the cathode 40 prior to the application of a pulse of energy from the power supply 30. This pulse of energy is provided with a time duration commensurate with the voltage of the power supply 30 and the thickness and composition of a subject 54 which is to be photographed by the system 20. The target 38 is thin enough, on the order of one-half mil, so that X-rays emitted from its top surface can pass through the target 38 towards the subject 54; the target 38 is thick enough to stop the incident electrons.

The use of the target 38 and substrate 36 provides for simplicity in mechanical design since the well-known rotating anode is not required. In addition, the thin depth of the target 38 coupled with the good thermal conductivity of the substrate 36 provides increased cooling of the target 38 and greater power handling capability over other forms of X-ray tubes.

A fluorescer 56 consisting of a layer of a fluorescent material, such as an oxide of cerium, commonly known as ceria, and a zone plate 58, such as that which is shown in FIG. 7, are mounted exteriorally to the substrate 36 by means of nuts 60 and bolts 62 which urge together flanges 64 which extend from a bezel 66 and the base 34. The bezel 66 surrounds the fluorescer 56 and the zone plate 58 for nesting them in position adjacent the substrate 36. A window 68 which is composed of a low atomic number material, such as aluminum, which is transparent to X-rays is mounted at one end of the housing 26 for retaining the oil 28 within the housing 26 while permitting the propagation of radiation from the X-ray tube 24 to the subject 54.

A half-tone screen 70, which is further shown in FIG. 7, is positioned between the zone plate 58 and the subject 54, the position of the screen 70 being closer to the subject 54 than to the zone plate 58, for presenting to the incident radiation a modified view of the subject 54 which is seen to be apparently broken up into small regions analogous to a mosaic which has a relatively high spatial frequency spectrum. Such a spectrum cooperates advantageously with the zone plate 58 to provide a superior image, as will be disclosed in FIG. 6, than does the low frequency spectrum associated with the subject 54. The rays of X-radiation as modulated by the zone plate 58, the screen 70 and the subject 54 impinge upon a photographic plate 72 for providing a coded image similar to a hologram on the photographic plate 72.

As an example of the use of the system 20, it is convenient to consider the situation where angiography is utilized for examining a human subject in which case the subject 54 would be that portion of the human subject under observation. In angiography, a dye such as iodine is commonly administered to the patient for purposes of absorbing X-radiation to better define the shadow cast by an organ or blood vessel as compared with the shadow of other tissue which has absorbed a differing amount of the iodine dye. The choice of cerium for use in the fluorescer 56 is based on the fact that the X-ray emission spectrum of cerium advantageously matches the absorption spectrum of iodine. The fluorescent emission lines of cerium occur at essentially the peak of the X-ray absorption curve for iodine in the well-known graphical portrayal of the X-ray absorption of iodine as a function of the energy in electron volts of the radiation to be absorbed. Radiation having energies far removed from the peak absorption energy of iodine is absorbed substantially less. However, only relatively small amounts of such energies are emitted from the fluorescer 56 since the main source of radiation from the fluorescer 56 is its own fluorescent radiation while the radiation emanating from the target 38 is substantially absorbed by the fluorescer 56. A thin foil of the fluorescent material substantially attenuates the radiation from the target 38 but is essentially transparent to its own fluorescent radiation. In this way, the choice of cerium in the fluorescer and iodine in the subject cooperate to provide a well-defined image of the patient, the definition being due to the monochromaticity of the radiation incident upon the patient and the choice of the energy or frequency of the incident radiation to be equal to the energy or frequency at the peak of the absorption spectrum of the dye which has been administered to the patient.

Referring now to FIG. 2 there is seen an alternative embodiment of the X-ray tube 24 of FIG. 1, this embodiment being designated by the legend 24A. The X-ray tube 24A is seen to comprise a non-contacting grid 74 having the form of an annulus or cylinder with its axis coinciding with the axis of the tube 24A. The cathode 40 of FIG. 1 is here modified as shown by the cathode 40A to provide the paths of emission of electrons which are more readily directed by the grid 74 to uniformly illuminate the target 38 which is seen to be deposited on the substrate 36 as was done in FIG. 1. The diameter of the grid 74 is approximately equal to the spacing of the grid 74 from the cathode 40A. Use of the grid 74 provides better control over the beam modulation to provide sharper pulses since the power supply 30 is no longer required to pulse on and pulse off the high voltage between the cathode 40A and the target 38. A well-known circuit indicated as grid pulser 76 is utilized for applying a difference of potential between the cathode 40A and the grid 74 to accomplish a modulation of the beam of electrons.

Referring now to FIG. 3 there is seen the lower portion of the X-ray tube 24 of FIG. 1 to which is affixed, in addition to the zone plate 58, a moire mask assembly 78 comprising an upper mask 80 and lower mask 82 which are placed between the substrate 36 and the zone plate 58. The upper and lower masks 80 and 82 are supported by bezels 84 which are seen to be nested between the bezel 66 and the base 34, the moire mask assembly 78 and the zone plate 58 being held in position relative to the base 34 by means of the nuts 60 and bolts 62 which interconnect the flanges 64. The orientation of the mask assembly 78, the zone plate 58 and the half-tone screen 70 of FIG. 1 will be described hereinafter with reference to FIG. 7.

The masks 80 and 82, as well as the zone plate 58, are readily fabricated by depositing a layer of material, such as lead or a suitable carrier compound of lead which is opaque to radiation, upon a substrate 86 of radiation transmissive material, such as aluminum. Portions of the lead are etched away by well-known photo etching techniques to provide the desired geometrical shape to the upper mask 80, the lower mask 82 and the zone plate 58.

In FIG. 3, the fluorescer 56 is supported by the bezel 66 in contact with the zone plate 58 as was done in FIG. 1. The mask assembly 78 provides shadows of the radiation emitted by the target 38 and incident upon the fluorescer 56. In particular, it is noted that opaque section 88 of the upper mask 80 and opaque sections 90 of the lower mask 82 are so aligned as to block those rays of radiation which are parallel to the axis of the housing 26. In this embodiment of the invention, the width of each opaque section 88 is equal to the width of each opaque section 90. Thus it is seen that while substantially no rays of radiation can propagate along the axial direction, rays of radiation can propagate at an angle inclined to the axis by passing between the opaque sections 88 and 90, as is indicated by arrow 91. In this way, the fluorescer 56 is illuminated by radiant energy emitted by the target 38 while substantially none of that energy propagates through the fluorescer 56 in the axial direction. Thus, with reference to both FIGS. 1 and 3, it is seen that substantially only the fluorescent radiation of the fluorescer 56 can reach the subject 54 while the primary radiation emitted by the target 38 passing through the mask assembly 78 and the fluorescer 56 does not impinge upon the subject 54 since such radiation is angled with respect to the axis of the generator 22 in view of the blockage provided by the mask assembly 78. Accordingly, it is seen that the introduction of the mask assembly 78 into the space between the fluorescer 56 and the target 38 has increased the monochromaticity of the radiation impinging upon the subject 54 since substantially only the fluorescent radiation of the fluorescer 56 radiates in the direction of the subject 54 while the primary radiation from the target 38 is inhibited from propagating in a direction towards the subject 54.

Referring now to FIG. 4 there is seen an alternative embodiment of the invention wherein an X-ray tube 92 is enclosed within a housing 94 with an electrically insulating layer of oil 96 interposed between the housing 94 and a glass envelope 98 of the X-ray tube 92. An aluminum substrate 100 is sealed to the envelope 98 and forms the base of the X-ray tube 92. The substrate 100 differs from the substrate 36 of FIG. 1 in that the substrate 100 has serrated edges 102 which are inclined at an angle to the axis of the housing 94. An X-ray target 104 is plated onto the serrated edges 102 in a manner analogous to the plating of the target 38 of FIG. 1 to its substrate 36. The thickness of the plating of the target 104 is substantially the same as the thickness of the plating of the target 38 of FIG. 1. Radiation directed outwardly from the tube 92 is emitted from the target 104 at an angle to the serrated edges 102, such an angle being preferably on the order of 80° to 85° relative to a normal, to a serrated edge 102. As will be disclosed with reference to FIGS. 8 and 9, the spectra of radiation emitted from the surface of the target 104 varies with the angle of observation of the radiation relative to the surface from which the radiation is emitted. As will be seen, X-radiation emitted at glancing angles of approximately 5° to 10° contains a higher percentage of the fluorescent X-ray lines relative to the entire spectrum of the X-radiation than is the case with radiation observed at other angles relative to the surface of the emitting target. Also, bremsstrahlung generated within the target 104 is attenuated in the axial direction because of the increased depth of the target material as measured along the tube axis. This further reduces the amount of bremsstrahlung reaching the zone plate 58. Accordingly, the observed radiation which, in the embodiment of FIG. 4 is seen at an orientation substantially parallel to the axis of the tube 92, is of enhanced monochromaticity which, as has been discussed earlier, is most useful for roentgenography.

The embodiment of FIG. 4 illustrates an alternative way of applying the difference of potential between the cathode 40 and the anode or target 104. Here the substrate 100 is utilized in sealing off the chamber of oil 96 so that the flanges 64 are mounted externally to the insulating oil 96 rather than being enclosed by the oil, as was done in the embodiments of FIGS. 1–3. The wires 44 and 46 couple the power supply 30 respectively to the cathode 40 and the substrate 100 in a manner analogous to that utilized in connecting the power supply 30 in FIG. 1. In FIG. 4, the wire 46 is grounded so that the substrate 100 and the target 104 are also at ground. This permits attachment and detachment of the moire mask assembly 78, the fluorescer 56 and the zone plate 58 whenever desired by an operator of this equipment as may be required for examining various parts of human patients. Since the difference of potential provided by the power supply **30** may be as high as 150 kilovolts, an especially designed filament transformer **106** which is sufficiently insulated to withstand 150 kilovolts between its primary and secondary windings is utilized. As seen in FIG. **4**, the center tap of the primary winding of the transformer **106** is grounded to the wire **46** while the center tap of the secondary winding of the transformer **106** is coupled to the high voltage on wire **44**.

The moire mask assembly **78** and the fluorescer **56** are utilized in FIG. **4** in the same manner as disclosed previously in FIG. **3** for enhancing the monochromaticity of the radiant energy emitted by the fluorescer **56**. The structure of FIG. **4** provides further enhancement over that of FIG. **3** since less bremsstrahlung propagates from the target **104** in the direction of the zone plate **58**.

Referring now to FIG. **5** there is seen a further modification of the tube **92** of FIG. **4**, the X-ray tube in FIG. **5** being designated by the legend **92A** while its housing is designated by the legend **94A**. The tube **92A** incorporates a target **108** which is deposited on a substrate **110** both of which have surfaces inclined in the manner of the serrated edges **102** of FIG. **4**. The target **108** is composed of a 20–40 micron thick layer of the same material of which the fluorescer **56** of FIG. **1** is composed, namely, one of the lower atomic numbered X-radiating elements such as cerium or molybdenum which produce a more pronounced K emission line than a high atomic numbered element such as tungsten. This results in a higher intensity of the softer X-rays, typically 34 keV as used in mammography, being produced directly in response to electron bombardment of the target **108** than is obtained with the target **38** of FIG. **1**. For example, in the case of a 20 micron thick layer of molybdenum, the k_{α} emission lines are at 17.5 keV. With illumination by 35–40 keV electrons, more than 95 percent of the total radiation is concentration in the range 14–20 keV photon energy. Illumination of a 40 micron thick layer of cerium with 70 keV electrons generates a spectrum, as viewed at an angle of 80° relative to a normal to the surface of the cerium layer, which contains 70 percent of its energy in the range 33–40 keV. This cerium emission spectrum corresponds to the maximum absorption region of the iodine spectrum thus making iodine an ideal radiographic dye for use with a cerium X-ray source.

In lieu of the serrations, the inclining of the surfaces is accomplished in the tube **92A** by providing the substrate **110** and the target **108** with a frusto-conical shape. It is noted that the inclined surfaces of the target **108**, as well as the target **104** of FIG. **4**, have the further advantage of enlarging the total area illuminated by the electrons from the cathode **40** with the result that a greater intensity of X-rays is produced. The substrate **110** is seen to have a rim **112** which is sealingly mated to a glass envelope **114** for providing a vacuum in the interior of the tube **92A**. A zone plate **58** is shown affixed to the rim **112** by means of nuts **60** and bolts **62** which couple the flanges **64** in a manner analogous to that disclosed with reference to FIG. **3**.

Referring now to FIG. **6** there is seen a diagrammatic representation of an optical system **116** utilized in reconstructing an image on a screen (or film plate) **118** from the coded photograph or hologram on the film plate **72**, seen here and also in FIG. **1**. The optical system **116** comprises a light source **120**, which is advantageously a laser providing coherent illumination, a converging lens **122** which converges the rays of light through an iris **124** whereupon they impinge upon a second converging lens **126** which brings the light rays to a focus at focal point **128**. The photographic plate **72** of FIG. **1** is developed and then placed behind the lens **126** so that the rays of light exiting from the lens **126** pass through the photographic plate **72** on their way to the focal point **128**. A telescope **130** comprising plano-convex lens **132** and converging lens **134** is angled along axis **136** relative to the axis of the lens **126**. The telescope **130** observes diffracted light passing in the general direction of the axis **136** and through an iris **138** to image this light upon the screen **118**. The optical system **116** is utilized for decoding images formed with a zone plate **58**, in FIG. **1**, having the form of an off-axis Fresnel pattern. If a zone plate utilizing some other modulation pattern is employed in the system **20** of FIG. **1**, another form of decoding or matched filtering such as that disclosed in the aforementioned patent to Barrett is utilized. The orientation of the telescope **130** along the angled axis **136** corresponds with the off-axis focusing of an off-axis Fresnel plate. The light which is brought to a focus at the focal point **128** is blocked by the opaque portion of the iris **138** so as to form no portion of the reconstructed image on the screen **118**. As is apparent from FIG. **6**, the use of an off-axis Fresnel pattern zone plate provides a coded image on the photographic plate **72** which can be advantageously decoded with relatively few optical elements.

Referring now to FIG. **7** there is shown a partial view of the system **20** of FIGS. **1** and **3** showing only the upper mask **80**, the zone plate **58** having a Fresnel pattern thereon, and the half-tone screen **70** shown positioned along a common axis **140** which axis coincides with the axis of the housing **26** of FIG. **1**. In FIG. **7** it is seen that the lines of the Fresnel pattern of the zone plate **58** are substantially parallel to the lines of the half-tone screen **70** while the lines of the upper mask **80** (as well as of the lower mask **82**) are perpendicular to the lines of the half-tone screen **70**. These orientations have been chosen since they have produced good images of the subject **54** of FIG. **1**.

The half-tone screen **70** may be formed by depositing a material containing lead upon a substrate, as was done with the zone plate **58**, or by making a filamentary tape in which alternate filaments or threads are composed of lead-bearing material or other material opaque to X-rays, with these leaded filaments being interleaved among filaments of a transparent material, such as nylon. The filamentary tape is then mounted on a frame at the edges of the filamentary tape (not shown) or, alternatively, is mounted on a substrate transparent to X-radiation. Other geometrical patterns may be utilized in forming the half-tone screen **70**, such as a checkerboard pattern or a pattern comprised of one or more Fresnel patterns such as that utilized in the zone plate **58**.

Referring now to FIG. **8** there is seen a graph portraying the purity of the X-ray spectrum obtained from a fluorescer, such as the fluorescer **56** of FIG. **2**, as a function of the viewing angle by which the emitted radiation is observed, the viewing angle being measured from the normal to the surface of the fluorescer **56**. FIG. **8** represents data obtained for a fluorescer **56** comprised of a 20 micron (micrometer) thick layer of molybdenum while FIG. 9 shows a similar graph obtained for a 40 micron thick layer of cerium. Also shown in FIGS. 8 and 9 are the intensity of the radiation of the k_α lines and the bremsstrahlung. The curve representing the purity represents the intensity measured at the k_α lines divided by the intensities of all the radiation, that being the radiation of the bremsstrahlung plus the k_α line radiations. It is noted that the purity curve peaks up in the range of approximately 80° to 85° and as was explained earlier with reference to FIGS. 4 and 5, this peaking effect on the purity curve is one of the reasons for inclining the surface of the target 38 relative to the axis of the X-ray tube. Thus, the purity curve is a measure of the monochromaticity of the emitted radiation.

Referring again to FIG. 6 it is noted that a standard X-ray film plate is of rather large size, on the order of 10 inches by 12 inches, and that this size plate would require large lenses, such as the lens **126**, for illuminating the photographic plate **72**. Accordingly, the photographic plate **72** may be placed in a light box wherein it is illuminated with diffused light and photographed to produce a reduced size photographic plate with a reduction factor of approximately 20:1. This permits the use of a standard size lens for the lens **126**.

It has also been found convenient to provide a photographic plate which has been bleached. This is accomplished by placing the original photographic plate **72** in a light box wherein it is illuminated by diffused light and photographed onto a second photographic plate in which the photographic emulsion is supported by a glass plate. The second photographic plate is then developed in the usual manner subsequently immersed in a bleaching solution which replaces the opaque silver with a transparent salt. The bleached regions introduce a phase shift to light traversing the second photographic plate with the result that the second photographic plate is in the form of a phase modulated hologram rather than an amplitude modulated hologram. The second photographic plate is then utilized in the reconstruction system of FIG. 6 in the same manner as was done with the original photographic plate **72**. Use of the second photographic plate provides increased dynamic range to the reconstructed image on the screen **118**.

FIG. **10** shows apparatus for reducing the size of the coded image on the photographic plate **72**. The plate **72** is shown being carried by a conveyer belt **142** guided by rollers **144** into a photographic developing bath **146** after which it is photographed by a lamp **148** of diffused light, a lens **150** and a second plate **152** upon which is imaged a 20:1 reduction in size. A second bath (not shown) similar to bath **146** may be used for bleaching the second plate **52**.

The zone plate **58** of FIG. **1** having an off-axis Fresnel pattern utilizes a line spacing of approximately 50 lines per inch on the average. In situations where the half-tone screen **70** of FIG. **1** is positioned half way between the zone plate **58** and the photographic plate **72**, the half-tone screen is provided with a line density of 100 lines per inch. To ensure an adequate density of line spacing on the half-tone screen for high quality images, the line density for the half-tone screen is obtained by the following formulation, namely, multiplying the average spacing desity of the zone plate by a factor related to the relative spacings between the zone **58**, the screen **70** and the photographic plate **72**, this factor being the distance from the zone plate **58** to the plate **72** divided by the distance between the zone plate **58** and the half-tone screen **70**.

While the present zone plate **58** has a diameter typically on the order of 10 inches with an average line spacing density of 50 lines per inch, other size zone plates may be utilized. In particular, it is noted that with zone plate configurations wherein the line spacing is substantially coarser than that utilized in the preferred embodiment of the invention, then the aforementioned reduction in size of the photographic plate **72** by the photographing thereof in a light box is necessary to ensure a high resolution image. With the aforementioned density of 50 lines per inch, such reduction is not necessary for resolution purposes but is recommended because it permits the utilization of standard size lenses.

It is understood that the above-described embodiments of the invention are illustrative only and that modifications thereof will occur to those skilled in the art. Accordingly, it is desired that this invention is not to be limited to the embodiments disclosed herein but is to be limited only as defined by the appended claims.

What is claimed is:

1. A X-ray system comprising:
means for generating X-rays;
means for improving the monochromaticity of said X-rays, said improving means comprising a mask assembly having a first and a second mask, each of said masks having regions relatively opaque to X-radiation interspersed among regions relatively transparent to X-radiation, said second mask being spaced apart from said mask along an axis normal to a surface of said first mask, the opaque regions in one of said masks being in registration with the transparent regions of the other of said masks; and
means for spatially modulating said X-rays, said modulating means comprising regions of relative opacity to X-rays interspersed among regions having relative transparency to said X-rays, the spaces occupied by successive ones of a plurality of said opaque and said transparent regions being arranged in a monotonically decreasing order in a predetermined direction.

2. An X-ray system comprising:
means for generating X-rays;
means for improving the monochromaticity of said X-rays, said improving means comprising a layer of luminescent material positioned for illumination by said X-rays, said luminescent material providing luminescent X-rays in response to illumination by said X-rays of said generating means; and
means for spatially modulating said X-rays, said modulating means comprising regions of relative opacity to X-rays interspersed among regions having relative transparency to said X-rays, the spaces occupied by successive ones of a plurality of said opaque and said transparent regions being arranged in a monotonically decreasing order in a predetermined direction.

3. A system according to claim **2** wherein said improving means comprises a mask assembly having first and second masks, each of said masks having regions relatively opaque to X-radiation interspersed among regions relatively transparent to X-radiation, said first and said second masks being spaced apart along an axis normal to a surface of said first mask, the opaque areas of one of said masks being in registration with the transparent areas of the other of said masks to inhibit the propagation of radiation in the general direction of said axis.

4. An X-ray system according to claim **1** wherein said generating means comprises a layer of X-ray emitting material deposited on a substrate substantially transparent to said X-radiation, radiation being emitted by said emitting material in response to illumination of said emitting material by electrons.

5. An X-ray system comprising:

means for generating X-rays;

means for improving the monochromaticity of said X-rays;

means for spatially modulating said X-rays, said modulating means comprising regions of relative opacity to X-rays interspersed among regions having relative transparency to said X-rays, the spaces occupied by successive ones of a plurality of said opaque and said transparent regions being arranged in a monotonically decreasing order in a predetermined direction; and wherein

said generating means comprises a layer of X-ray emitting material deposited on a substrate substantially transparent to said X-radiation, radiation being emitted by said emitting material in response to illumination of said emitting material by electrons, and wherein said electrons illuminate said emissive material on a side of said layer opposite said substrate, said X-rays emitted by said emissive material propagating through said substrate, said substrate having a serrated surface contiguous to said layer of X-ray emitting material, the surfaces of said serrations being angled to a plane of said modulating means to provide for X-ray emission in the direction of said modulating means having a substantially monochromatic spectrum.

6. A system according to claim **5** wherein said transparent substrate has a generally conically shaped surface on the side adjacent said X-ray emitting material.

7. A system according to claim **5** wherein said generating means has a window through which X-rays are emitted, and said substrate has a surface contiguous said layer of emitting material and inclined at an angle relative to said window.

8. A system according to claim **7** wherein said improving means comprises a mask assembly having a first and a second mask, each of said masks having regions relatively opaque to X-radiation interspersed among regions relatively transparent to X-radiation, said second mask being spaced apart from said first mask along an axis normal to a surface of said first mask, the opaque areas in one of said masks being in registration with the transparent areas of the other of said masks.

9. A system according to claim **8** wherein said spatial modulating means is a zone plate having regions relatively opaque to X-radiation arranged on a transparent substrate in the form of an off-axis Fresnel pattern.

10. An X-ray system comprising:

means for generating X-rays;

means for improving the monochromaticity of said X-rays, said improving means comprising a layer of luminescent material positioned for illumination by said X-rays, said luminescent material providing luminescent X-rays in response to illumination by said X-rays of said generating means;

means for a spatially modulating said X-rays, said modulating means comprising regions of relative opacity to X-rays interspersed among regions having relative transparency to said X-rays, the depth of each of said regions being less than the width of each of said regions to permit X-rays emanating from spaced apart regions of said generating means and passing through separate ones of said transparent regions of said modulating means to impinge upon a common region of space behind said modulating means; and

wherein said spatial modulating means is a zone plate having regions opaque to X-radiation arranged on a substrate transparent to X-radiation in the form of an off-axis Fresnel pattern.

11. A system according to claim **10** further comprising means for recording a coded image of a subject illuminated by said spatially modulated radiation, said recording means being spaced apart from said spatially modulating means.

12. A system according to claim **11** wherein said recording means includes means for reducing the size of said coded image.

13. A system according to claim **11** further comprising means for reconstructing an image of said subject from said coded image, said reconstructing means including:

means for focusing rays of light through said coded image to a point on an axis passing through said coded image; and

means for viewing radiation emitted from said coded image at an angle to said axis.

14. In combination:

means for generating high energy radiation comprising a relatively thin member of fluorescent material having a longitudinal dimension many times greater than its depth, said generating means further comprising means for uniformly exciting said fluorescent material with electrons of sufficiently high energy to excite radiation from said fluorescent material, and means coupled to said exciting means for adjusting said electron energy to be approximately equal to the energy of a fluorescent emission of said material to enhance the monochromaticity of said radiation; and

means for spatially modulating said radiation, said modulating means being a relatively thin member spaced relative to said generating means for intercepting said radiation, said modulating means having a multiplicity of regions opaque to said radiation and transparent to said radiation, each of said regions being of differing sizes to provide a broad band spatial frequency distribution to said radiation.

15. A combination according to claim **14** wherein said member of fluorescent material is positioned with an orientation inclined relative to said modulating member to provide for increased monochromaticity to the spectrum of X-radiation emitted in the direction of said modulating member.

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