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[54] **MONOCHROMATIC X-RAY GENERATOR**

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

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[52] **U.S. Cl.** **250/493**; 313/330

[51] **Int. Cl.** **H01j 35/10**

[58] **Field of Search** 250/403, 419, 503, 493, 250/272, 273; 313/330

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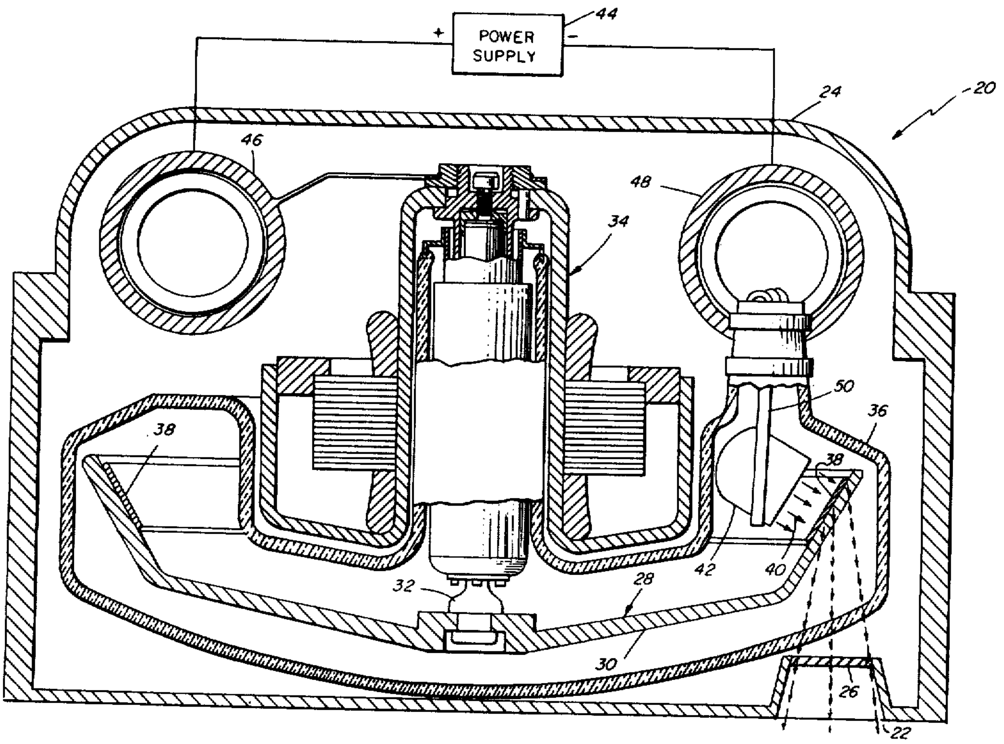
[57] **ABSTRACT**

An x-ray generator in which a moving target is illuminated by a beam of electrons having a predetermined energy. The target is in the form of a thin foil of a material which emits fluorescent x-radiation when illuminated by electrons having the predetermined energy. The target is sufficiently thin so that a substantial amount of the fluorescent radiation is emitted on the side opposite to the side being illuminated while bremsstrahlung radiation, to which the target is relatively opaque, is attenuated thereby providing for a greater percentage of radiation from the fluorescent portion of the spectrum. In addition, the target is inclined at an angle relative to an exit port of the generator for still greater attenuation of the bremsstrahlung with substantially no additional attenuation of the fluorescent radiation to which the target is substantially transparent. Highly monochromatic x-rays are thereby produced.

8 Claims, 6 Drawing Figures



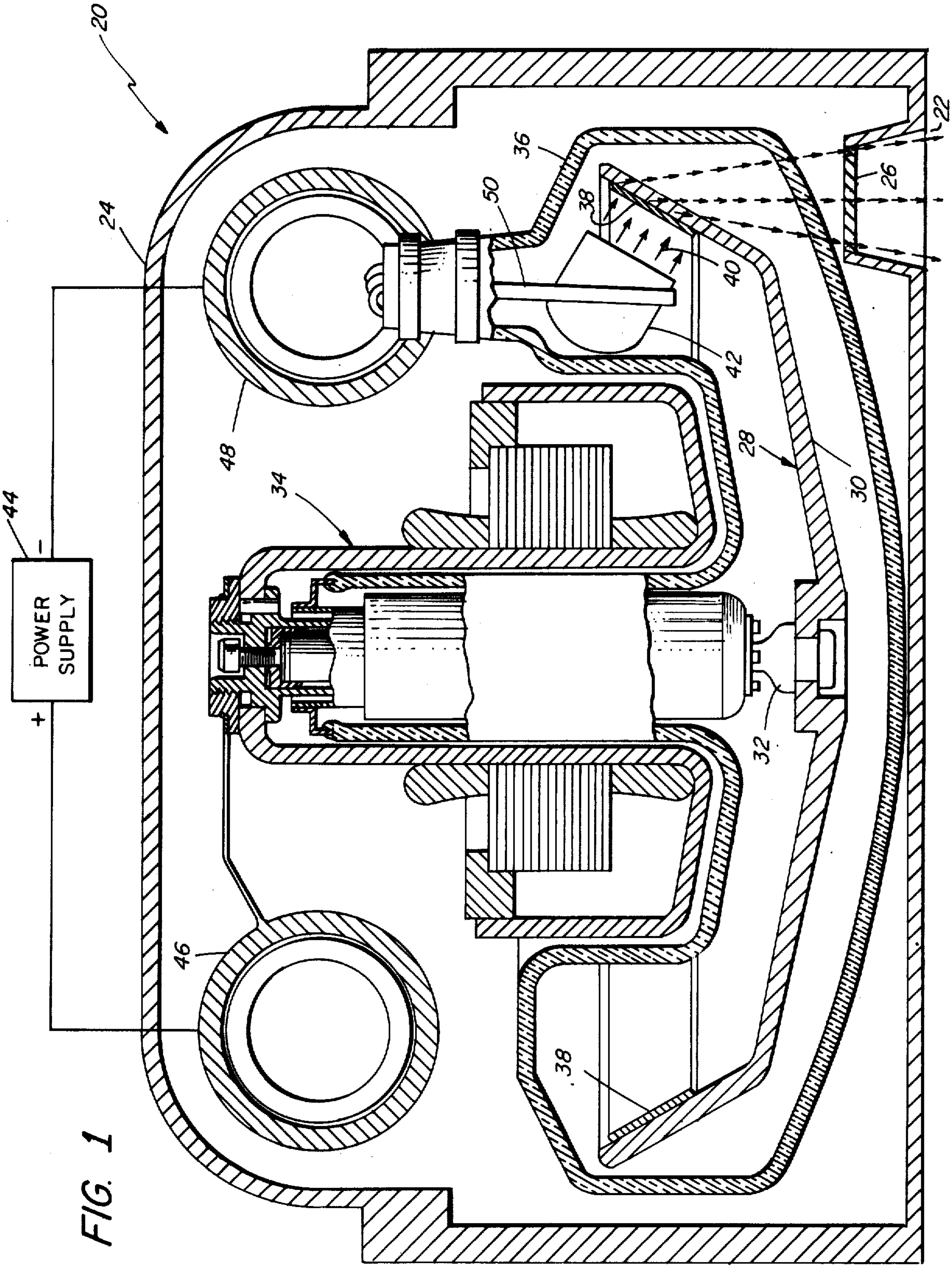


FIG. 1

FIG. 2

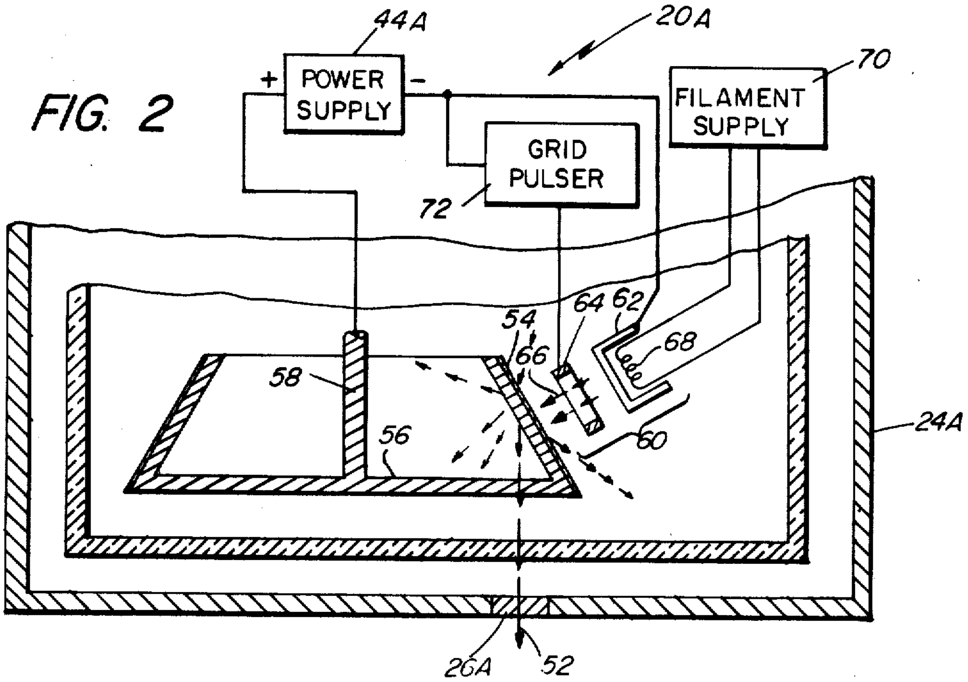


FIG. 3

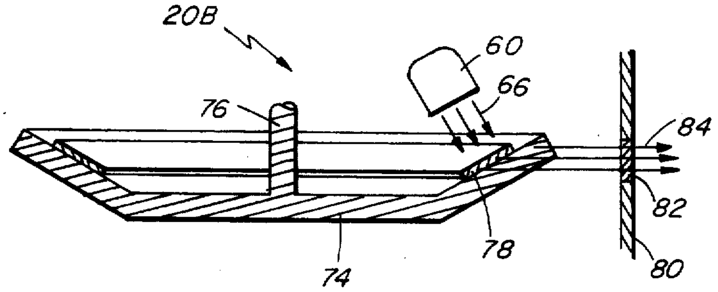
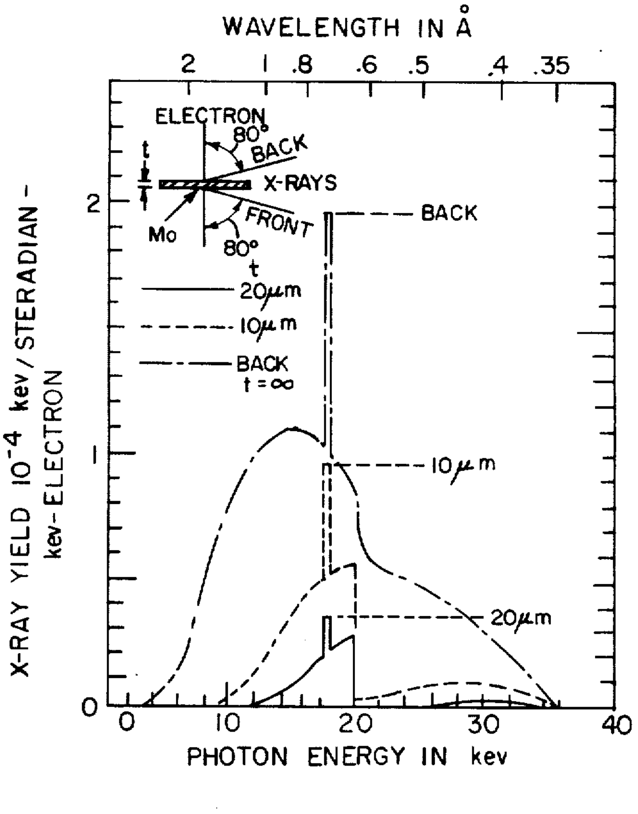


FIG. 4



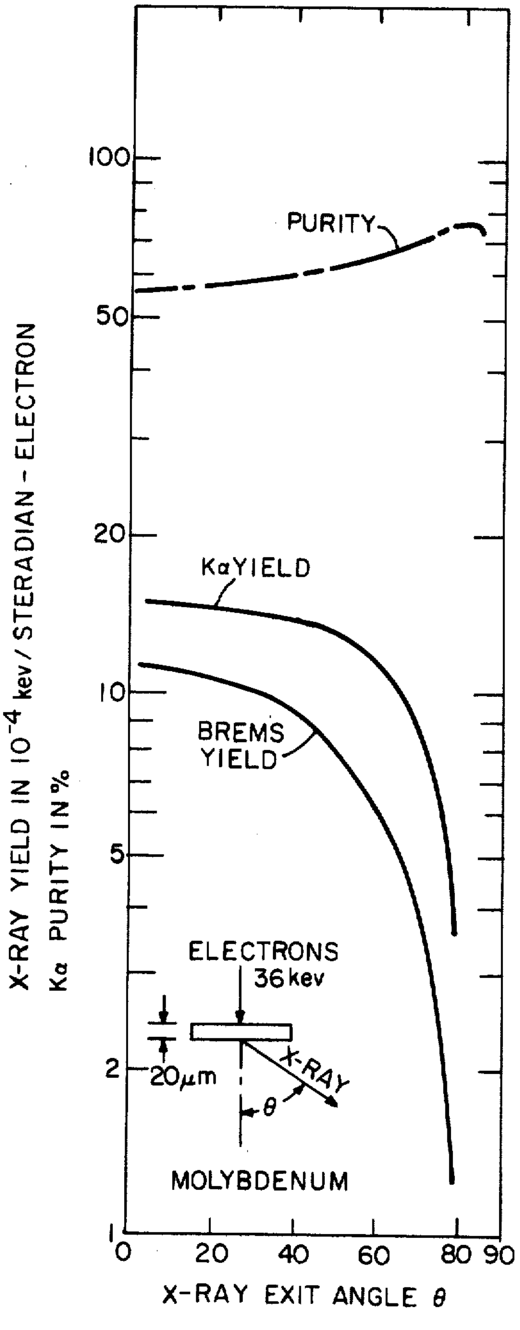

X-RAY YIELD IN 10^-4 kev / STERADIAN - ELECTRON
Kα PURITY IN %
100
50
20
10
5
2
1
PURITY
KαYIELD
BREMS YIELD
ELECTRONS
36kev
20μm
X-RAY
θ
MOLYBDENUM
0
20
40
60
80
90
X-RAY EXIT ANGLE θ

FIG. 5

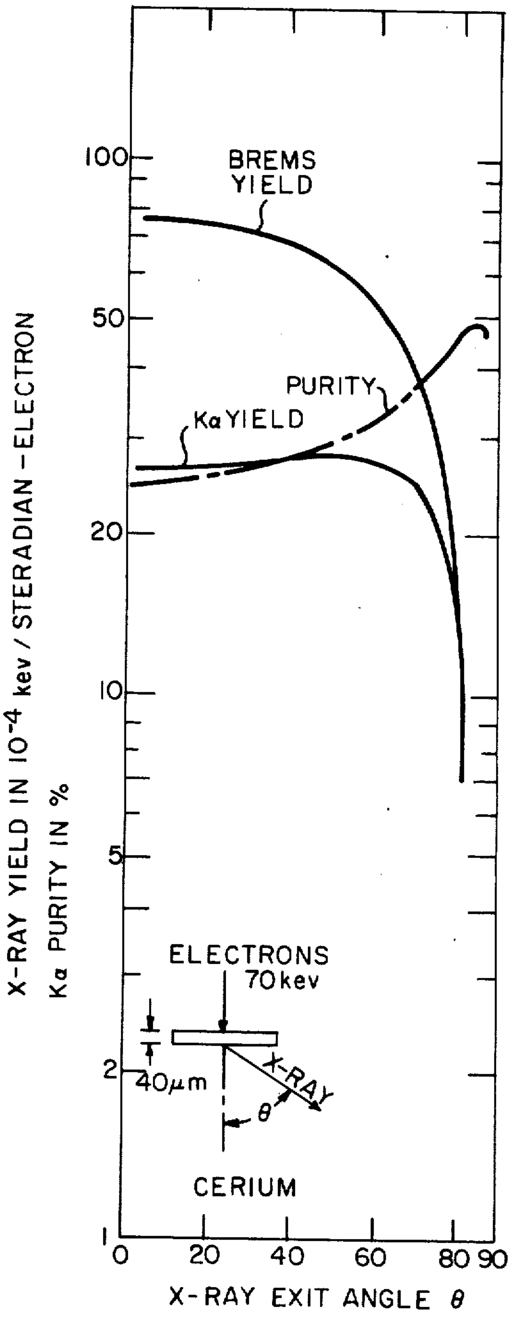

X-RAY YIELD IN 10^-4 kev / STERADIAN - ELECTRON
Kα PURITY IN %
100
50
20
10
5
2
1
BREMS YIELD
PURITY
KαYIELD
ELECTRONS
70kev
40μm
X-RAY
θ
CERIUM
0
20
40
60
80
90
X-RAY EXIT ANGLE θ

FIG. 6

MONOCHROMATIC X-RAY GENERATOR

BACKGROUND OF THE INVENTION

A standard form of x-ray generator utilizes a rotating anode or target, typically of a heavy element such as tungsten or gold, which is illuminated by a beam of electrons accelerating through a difference of potential between a cathode and the anode. The beam of electrons is focussed to impinge upon a small portion of the target to provide the generator with the characteristics of a point source of x-radiation. As is well known, a point source of radiation produces distinct roentgenographs or photographs while a broader source of radiation having a lower spatial frequency bandwidth provides less clear images.

A problem arises in that the beam of electrons impinging upon the target excites a broad spectrum of frequencies of x-radiation with the attendant less-than-optimal clarity of the roentgenographs. Ideally, roentgenographs should be taken with x-radiation of a single frequency, or monochromatic radiation, since the differing frequencies of a broad spectrum radiation interact differently with the material of a subject such as the flesh and bones of a human subject.

SUMMARY OF THE INVENTION

The aforementioned problem is overcome and other features are provided by an x-ray generator in accordance with the invention which provides increased monochromaticity to x-radiation emitted by a target illuminated by a beam of high energy electrons. The increased monochromaticity is attained by utilizing a target in the form of a thin foil or deposition, on the order of 10 to 40 micrometers, of a material such as cerium or molybdenum which have a pronounced fluorescent line in their radiation spectrum. The target is relatively opaque to bremsstrahlung having photon energies above the absorption edge while being relatively transparent to the fluorescent radiation and bremsstrahlung at lower values of photon energy. This difference in the relative attenuations of the radiations at frequencies above the fluorescent frequency as compared to radiations at and below the fluorescent frequency is utilized to provide improved monochromaticity to the radiation emitted from the generator as follows. The depth of the target is sufficiently thin to serve as a transmissive target which, when illuminated on one side thereof by the electrons, emits a substantial portion of the radiation from the surface of the target opposite the side which is illuminated by the electrons. A movable support is provided for orienting the target at an angle relative to an exit port of the generator so that radiation is emitted at a glancing angle to the surface of the target on the side of the target opposite the side illuminated by the electrons. Due to this oblique orientation of the target, radiation emitted in the direction of the exit port must traverse a greater distance within the material of the target, with the result that bremsstrahlung is severely attenuated while the fluorescent radiation emerges with substantially no attenuation. Soft x-rays having frequencies substantially lower than the fluorescent radiation are attenuated by a window in the exit port which is substantially opaque to these soft x-rays. Thus, the emergent radiation has a greatly reduced spectral width with substantial intensities of radiation being produced at and near to the fluorescent frequency. The supporting structure for the target is both thermally and electrically conductive to provide for the cooling of the target as well as the establishment of a difference of electrical potential between the target and a cathode.

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 a sectional view of an x-ray generator which comprises a target inclined at an oblique angle to a viewing port in accordance with the invention for providing monochromatic x-radiation;

FIG. **2** shows an embodiment of the invention where a source of x-rays is positioned off to the side of a rotating target in accordance with the invention;

FIG. **3** shows a third embodiment in which the beam of x-rays is parallel to the axis of rotation of the target while the exit port is positioned off to the side of the target;

FIG. **4** is a typical spectrum of x-radiation of a material exhibiting fluorescent radiation; and

FIGS. **5** and **6** show the angular dependency of the purity and relative intensity of the emitted radiation of molybdenum and cerium targets for use in the generator of FIG. **1**.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. **1** there is seen a generator **20** which provides monochromatic x-rays **22** in accordance with the invention. The generator **20** comprises a housing **24** of a metal such as lead which is opaque to x-radiation and which has a window **26** which serves as an exit port for the x-radiation and is composed of a material such as aluminum or beryllium. An anode assembly **28** includes a circular dish-shaped member **30** of a material such as beryllium or graphite which is transparent to x-radiation and is rotatably supported upon a shaft **32** which is, in turn, rotated by a motor **34**. The member **30** is enclosed by an evacuated envelope **36** of a material such as glass which is transparent to x-radiation. A thin target **38** in the form of a band is deposited upon the inner surface of the member **30** adjacent the periphery thereof and, upon rotation of the member **30**, is passed through a beam **40** of electrons which are accelerated from a cathode **42** to the target **38** under a difference of electrical potential established by a power supply **44** which is coupled via the terminals **46** and **48**, respectively, to the anode assembly **28** and the cathode **42**, the power supply **44** being shown diagrammatically.

The anode assembly **28** is electrically conducting for coupling the voltage of the power supply **44** to the target **38**. In addition, the dish-shaped member **30** is thermally conducting for cooling the target **38**. The cathode **42** is supported and positioned by a strut **50** which also contains electrical conductors (not shown) for coupling electrical voltage from the power supply **44** to the cathode **42**. In addition, the cathode **42** encloses a heater or filament (not shown) which is, in turn, energized by a filament supply (not shown).

In accordance with the invention, the target **38** is positioned by the member **30** at an oblique angle relative to the window **26**. Thereby, a portion of the radiation emitted by the target **38** in response to bombardment by the electron beam **40** is emitted in the direction of the window **26.** The depth of the target **38** is on the order of 10 to 40 micrometers which is a sufficient depth to stop the electrons of the beam **40.** X-radiation is produced at the surface of the target **38** facing the cathode **42,** with a portion of that radiation propagating through the target **38** to exit on its far side in the direction of the window **26.** Due to the oblique orientation of the target, which orientation is at typically an angle of 70°–85° depending on the particular material utilized in the target **38,** the rays emitted through the window **26** must pass through a distance wihtin the target **38** much greater than the depth of the target **38.** The target **38** is formed, in one embodiment of the invention, of molybdenum which is a source of strong fluorescent x-radiation. Upon illumination by the electron beam **40,** the target **38** provides both bremsstrahlung and fluorescent x-radiation, a portion of both of these radiations being emitted in the direction of the window **26.** Thus, both these radiations traverse a distance within the target **38** which is substantially greater than its depth, and, since the molybdenum is significantly more opaque to bremsstrahlung of photon energies greater than the photon energies of the fluorescent radiation, the bremsstrahlung is severely attenuated during its passage through the target **38** while the fluorescent radiation is not so attenuated. Softer x-rays having photon energies substantially below the energies of the fluorescent radiation are attenuated and substantially stopped by the aluminum window **26.** Thus, the x-rays **22** which have propagated through the window **26** are substantially monochromatic in that only the radiations at the fluorescent frequency and frequencies approximating the fluorescent frequency are passed through the window **26.**

Referring now to FIG. **2** there is seen a sectional view of a portion of an alternative embodiment of the generator **20** of FIG. **1,** here indicated by the reference numeral **20**A. X-rays **52** are seen exiting from a window **26**A in a housing **24**A which are similar to the window **26** and housing **24** of FIG. **1.** A target **54** is supported on a member **56** which is rotated about a shaft **58** with the aid of a suitable motor such as the motor **34** of FIG. **1.** The shaft **58** and member **56** are electrically conducting to couple voltage from the power supply **44**A to the target **54.** Electron optics **60** comprising a cathode **62** and grid **64** which is shown as an annular grid that does not intercept electrons of an electron beam **66** has provided for directing electrons of the electron beam **66** from the cathode **62** to the target **54.** A filament **68** or heater is energized by a filament supply **70** and heats the cathode **62** for emission of the electrons. A difference of potential is established between the cathode **62** and the target **54** by the power supply **44**A and a grid pulser circuit **72** provides a difference of potential between the grid **64** and the cathode **62** for pulsing ON and pulsing OFF the electron beam **66.**

In this embodiment of the invention, the target **54** is oriented at an oblique angle relative to the window **26**A in a manner analogous to the orientation of the target **38** relative to the window **26** of FIG. **1.** As in the embodiment of FIG. **1,** the axis of the electron beam is normal to the target. Radiation emitted from the target **54** of FIG. **2** propagates at a glancing angle relative to the surface of the target **54** thereby providing for attenuation of the bremsstrahlung as was explained with reference to FIG. **1.** Thus, it is seen that the x-rays **52** of FIG. **2** are monochromatic as are the x-rays **22** of FIG. **1.**

Referring now to FIG. **3** there is shown a partial view of a third embodiment of the generator **20** of FIG. **1,** here indicated by the legend **20B.** A member **74** is rotated about a shaft **76** and supports a target **78** positioned such that a normal to the surface of the target **78** is slightly angled relative to the axis of the shaft **76.** Electron optics **60** are positioned for directing an electron beam **66** normal to the surface of the target **78.** A housing **80,** partially shown, has a window **82** to serve as an exit port for x-rays **84** emitted at a glancing angle relative to the surface of the target **78.** And, for the same reasons as explained with reference to the embodiment of FIG. **2,** the x-rays **84** are highly monochromatic.

Referring now to FIG. **4** there is shown the spectrum of molybdenum as measured at an exit angle of 80° relative to a normal to the surface of the target such as the target **38** of FIG. **1.** As indicated on the figure, measurements are shown for target thicknesses of 10 micrometers and 20 micrometers as well as the back scatter situation corresponding to an infinite target thickness. The x-ray yield is plotted on the vertical axis while the photon energy of the x-rays is plotted on the horizontal axis. The fluorescent radiation occurs in a pair of lines at approximately 18 keV (kiloelectron volts). The highest purity is obtained for the measurement at a target thickness of 20 micrometers while the lowest purity is obtained for the back scatter condition where the purity is the ratio of the intensity of the radiation at the fluorescent frequencies to the total intensity of the radiation throughout the spectrum. A spectrum for cerium is similar to that for molybdenum.

As an example of the use of the generator **20** of FIG. **1,** it is convenient to consider the situation where angiography is utilized for examining a human subject. 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. In this situation, cerium or an oxide thereof known as ceria is chosen for use in the target **38** 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 (resulting from an electron of an outer shell of the cerium atom falling into a void in an inner shell due to bombardment by electrons from the cathode **42**) 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. In this way, the choice of cerium in the target **38** 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.

The target **38** comprises a material composed 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 angiography, being produced directly in response to electron bombardment of the target. For example, in the case of a **20** micron thick layer of nolybdenum, the $k\ \alpha$ emission lines are at 17.5 keV. With illumination by 35–40 keV electrons, more than 95% 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% 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.

Referring now to FIGS. **5** and **6** there are seen graphs portraying the purity of the x-ray spectrum obtained from an x-ray target, such as the target **38** of FIG. **1**, 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 target. FIG. **5** represents data obtained for a target comprised of a 20 micron (micrometer) thick layer of molybdenum while FIG. **6** shows a similar graph obtained for a 40 micron thick layer of cerium. Also shown in FIGS. **5** and **6** are the intensity of the radiation of the $k\ \alpha$ lines and the bremsstrahlung. The curve representing the purity represents the intensity measured at the $k\alpha$ lines divided by the total intensity of the bremsstrahlung plus the $k\ \alpha$ line radiations. It is noted that the purity curve peaks up in the range of approximately 70° to 85° this peaking effect on the purity curve being 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.

It is noted that the depth of the target has been selected to be thin enough to be substantially transparent to its own fluorescent radiation while having sufficient depth to attenuate the bremsstrahlung. In this film or foil-like target the width thereof is many times greater than its depth. By orienting the target at an oblique angle relative to the exit port, a thinner target may be utilized since those rays of radiation which are directed towards the exit port travel through a greater distance in the inclined target than do rays directed normally to the surface of the target. Improved monochromaticity has been observed in the situation in which a normal to the target surface is directed towards the exit port; however, still greater monochromaticity has been observed with the inclined target, apparently because bremsstrahlung directed normally to the surface and having energies above the fluorescent energy excite further sites of fluorescent radiation on or near the side of the target opposite the electron bombardment. Radiation emanating from these further sites experiences less attenuation than does the fluorescent radiation from the side illuminated by the electrons with the result that the obliquely oriented target provides still further monochromaticity.

A further advantage of the oblique orientation of the target is the relatively small projected area of the target as viewed from the exit port. Thus a relatively large area of the target may be illuminated by the electron beam providing greater power to the resulting radiation while the radiation exiting through the exit port appears to emanate from a relatively small source approximating a point source.

A further embodiment of the invention contemplates the fabrication of the target by diffusing the target material into the material of the supporting structure or substrate. For example, with respect to FIG. **1**, the target **38** would consist primarily of rhenium which would be diffused in an oven at 2500°C into the dish-shaped member **30** which would consist primarily of graphite. A major portion of the target would then be a mixture of rhenium in a graphite matrix which, because of the relatively low atomic number of a major constituent, the graphite, would permit penetration of the bombarding electrons to a greater depth than pure rhenium. The heat produced by the stopping of the electrons is thus distributed over a greater volume thus providing increased cooling capacity and permitting a higher intensity electron flux. The diffusion technique provides a strong bond between the target and substrate.

The dish-shaped member **30** of FIG. **1**, as has been described previously, is fabricated from a low atomic numbered material. Suitable materials are beryllium, boron, carbon, aluminum and combinations of these elements with each other and with other low atomic number elements. With respect to the fabrication of the target **38**, elements from zirconium (atomic number **40**) to palladium (atomic number **46**), or mixtures thereof, which produce radiographs of good contrast of soft tissue may be utilized. The lanthanides (atomic numbers **57** to **71**), or mixtures thereof, may also be utilized. These elements have fluorescent lines in their spectra which are readily absorbed in iodine or barium used in contrast agents.

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. An x-ray generator comprising:

means for generating a beam of electrons having a predetermined energy;

a target comprising a material which emits fluorescent x-radiation when illuminated on a first side thereof with electrons of said predetermined energy, the width of said target being many times greater than its depth, at least a portion of said radiation being emitted from a second side of said target opposite said first side;

a housing opaque to said radiation enclosing said target, said housing having a window transparent to said radiation;

means for moving said target through said beam, said moving means including means for orienting said target such that said second side thereof is angled relative to said window to permit only those rays of said radiation emitted at a glancing angle from said second side to exit said housing.

2. A generator according to claim **1** wherein the depth of said target is in the range of approximately 10 to 40 micrometers.

3. A generator according to claim **2** wherein the material of the target includes an element having an atomic number drawn from the range of atomic numbers of approximately 40–46 and 57–71.

4. In combination:

a target comprising a material which emits fluorescent x-radiation when illuminated on a first side thereof with electrons of a predetermined energy, at least a portion of said radiation being emitted from a second side of said target opposite said first side;

means for moving said target through said beam of electrons; and

window means for transmitting the portion of the rays of said radiation emitted in a glancing direction from said second side of said target.

5. A combination according to claim **4** wherein said selecting means comprises a housing opaque to said radiation enclosing said target, said housing having a window transparent to said radiation emitted in said direction.

6. A combination according to claim **5** wherein said moving means includes means for positioning said target such that said second side thereof is oriented obliquely relative to said window.

7. A combination according to claim **6** wherein said positioning means is in the form of a substrate for supporting said target, said target being formed by diffusing said fluorescent material into said substrate.

8. A combination according to claim **7** wherein said oblique orientation is an angle in the range of 70° to 85° between a normal to the surface of said second side of said target and a normal to the surface of said window.

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