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(54) **APPARATUS FOR MODIFYING ELECTRON BEAM ASPECT RATIO FOR X-RAY GENERATION**

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(51) **Int. Cl.**
H05G 1/52 (2006.01)

(52) **U.S. Cl.**
USPC **378/113**; 378/122; 378/136; 378/138

(58) **Field of Classification Search**
USPC 378/113, 121, 122, 136–138
See application file for complete search history.

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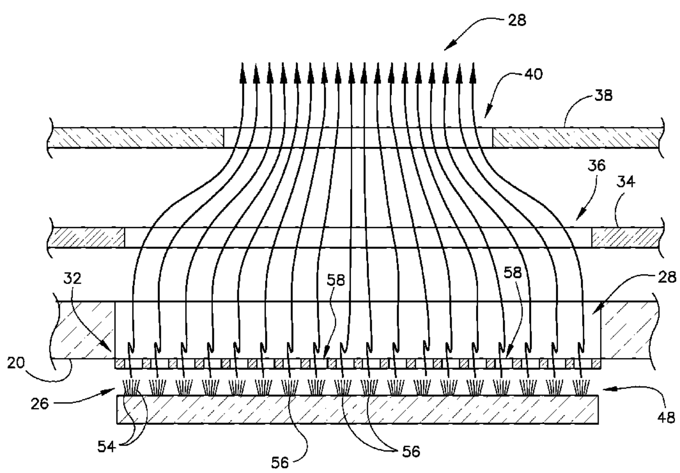
(57) **ABSTRACT**

An apparatus for modifying an aspect ratio of an electron beam to form a focal spot having a desired size and aspect ratio on a target anode is disclosed. The apparatus includes an emitter element configured to generate an electron beam having a first aspect ratio shape and an extraction electrode positioned adjacent to the emitter element to extract the electron beam out therefrom, the extraction electrode including an opening therethrough. The apparatus also includes at least one shaping electrode positioned to receive the electron beam after passing through the extraction electrode, the shaping electrode defining a non-circular aperture therein and being configured to provide at least one of shaping and focusing of the electron beam to have a second aspect ratio shape different from the first aspect ratio shape so as to form a focal spot having a desired size and aspect ratio on a target anode.

20 Claims, 8 Drawing Sheets



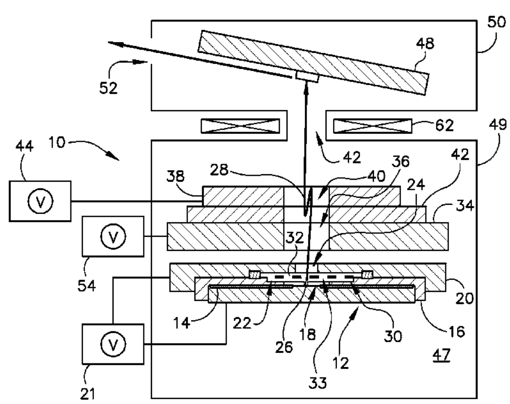


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FIG. 1

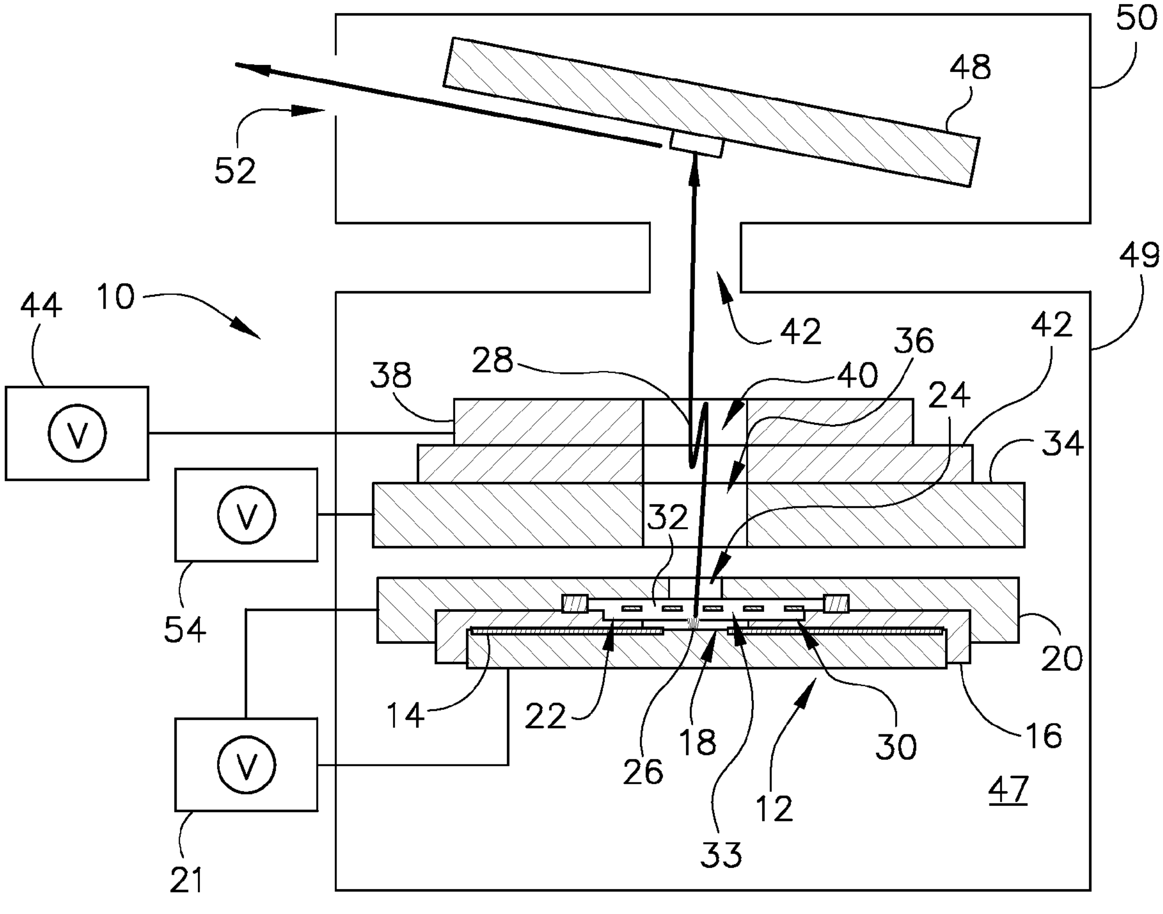
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FIG. 2

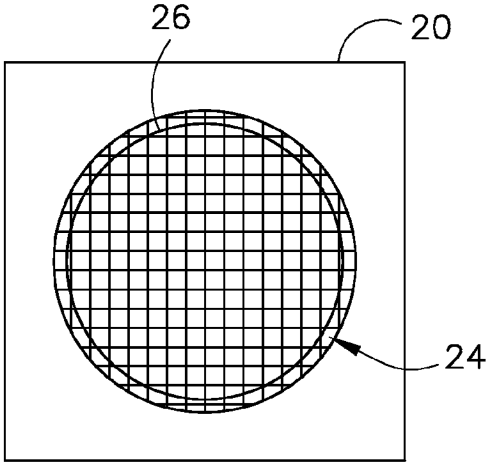


FIG. 3

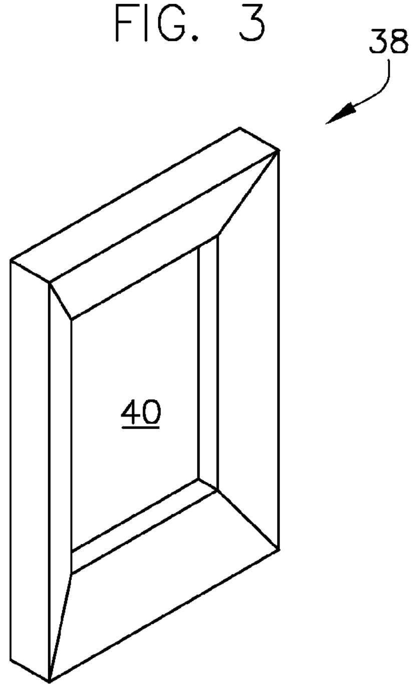


FIG. 4

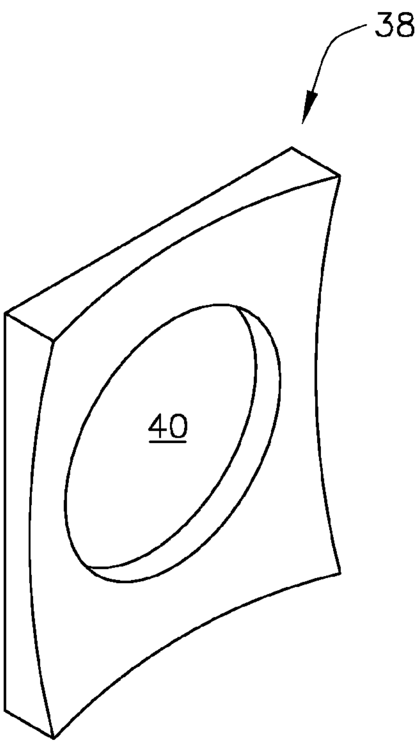
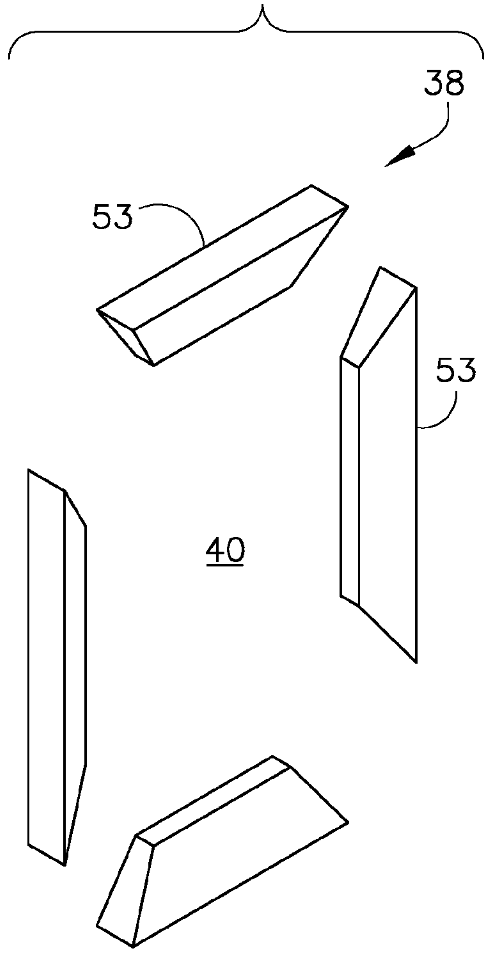


FIG. 5



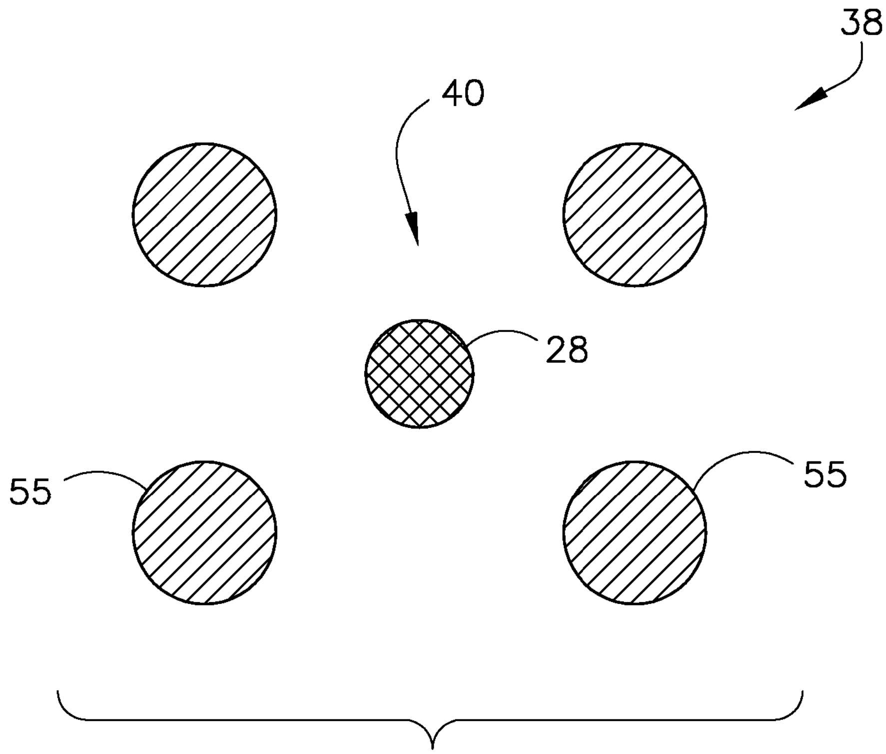


FIG. 6

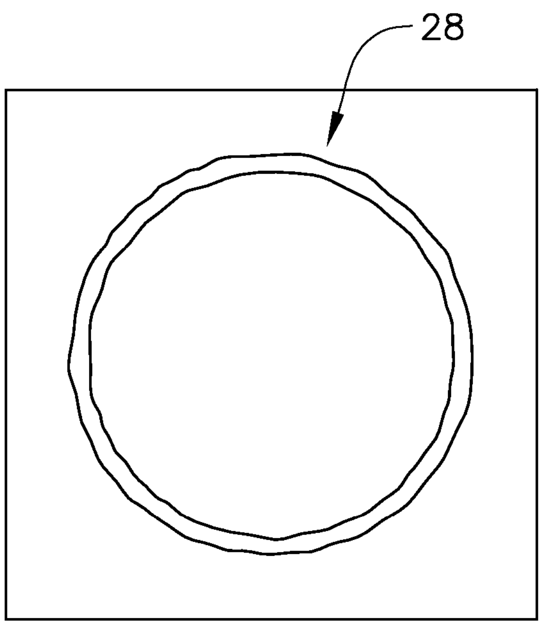


FIG. 7

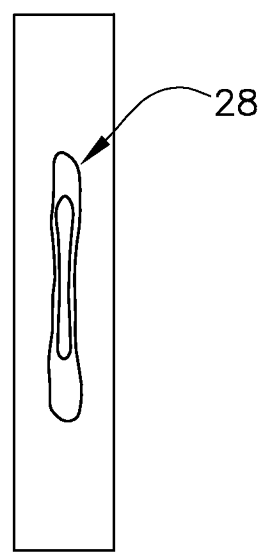


FIG. 8

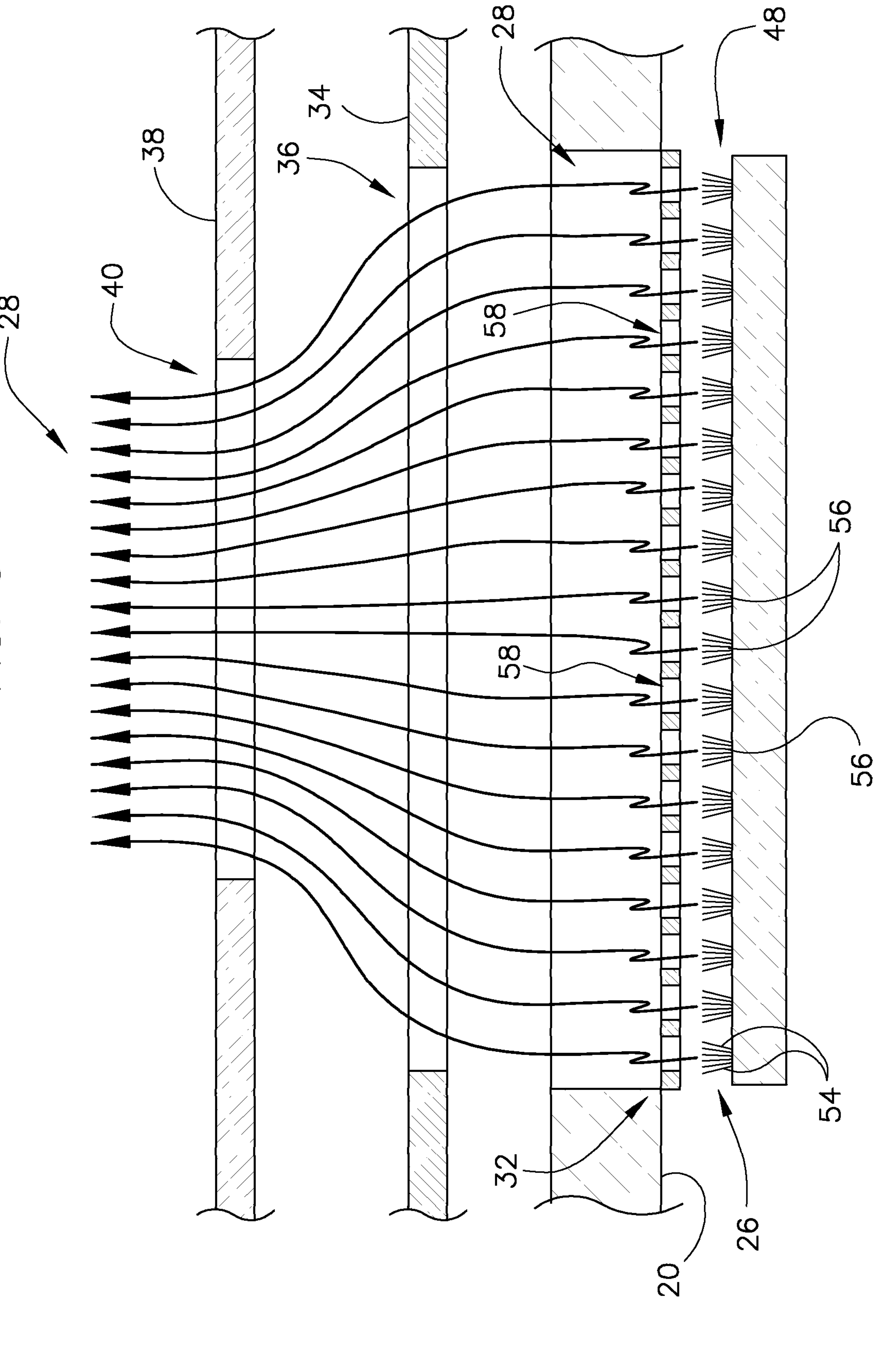


FIG. 9

FIG. 10

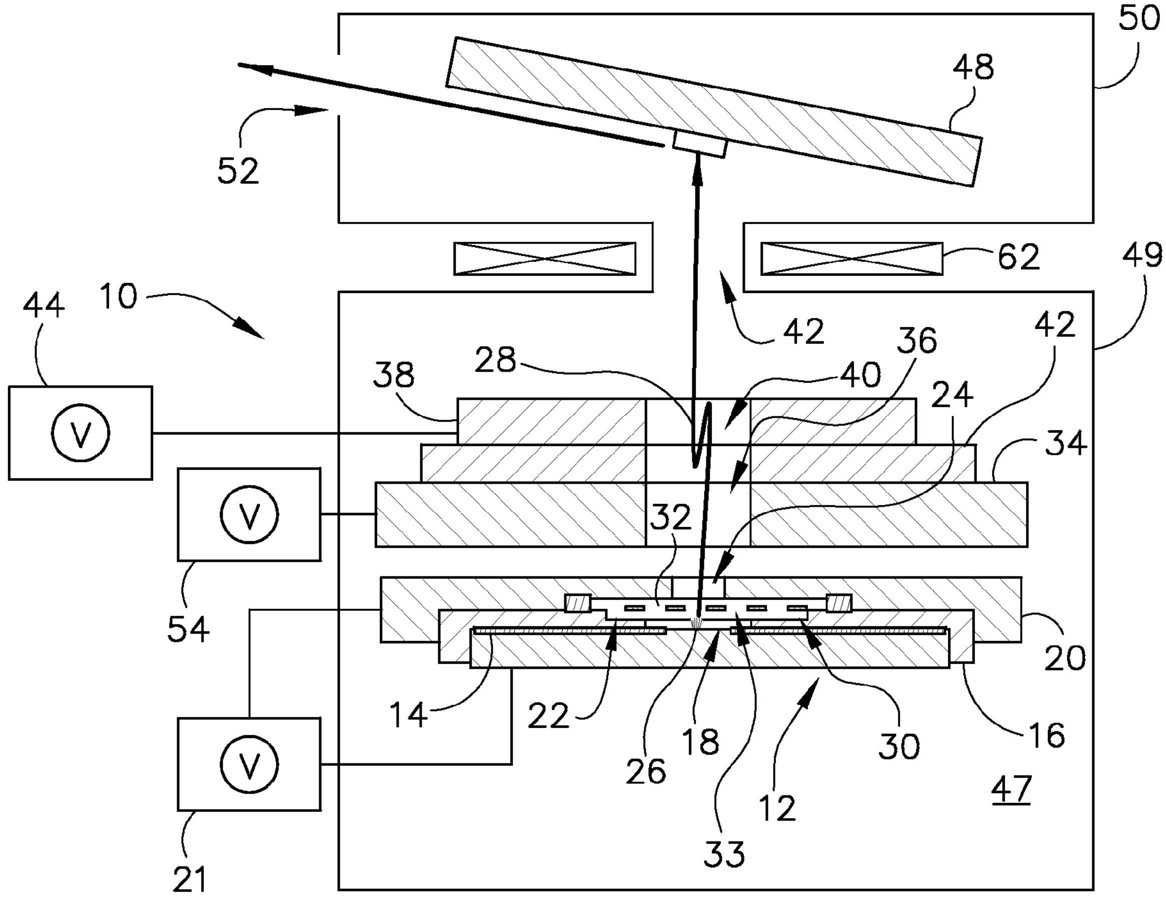

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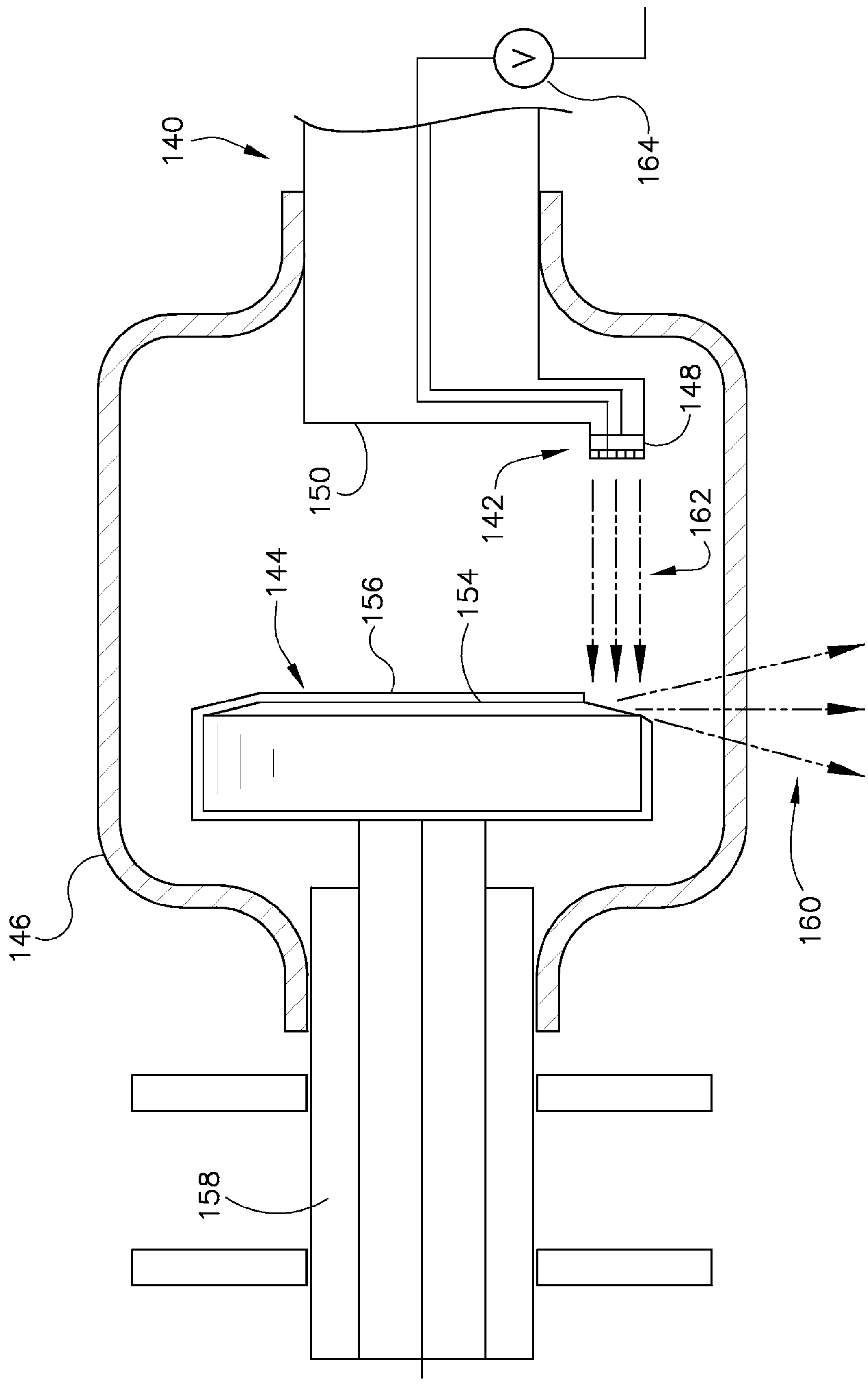
FIG. 11



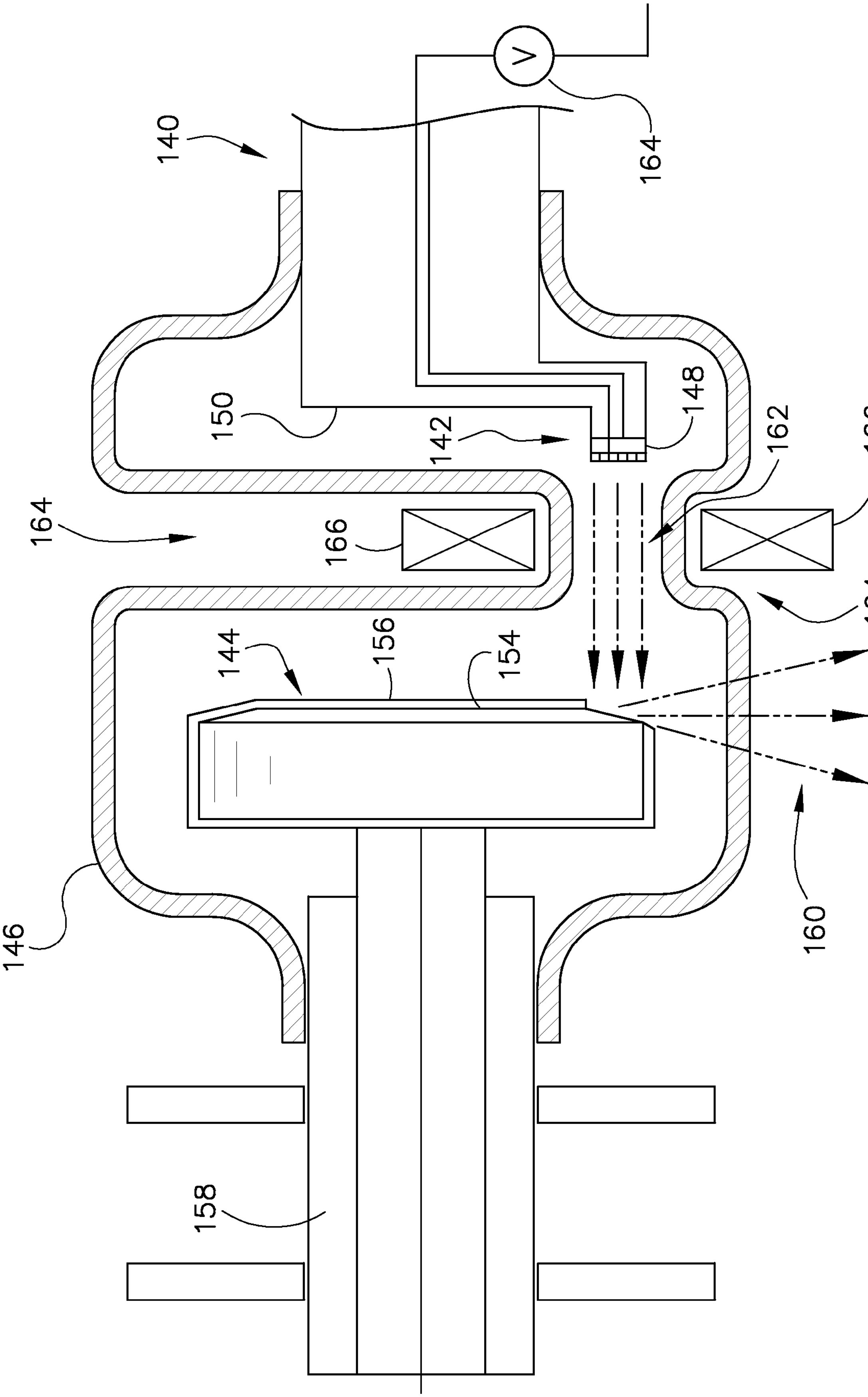


FIG. 12

FIG. 13

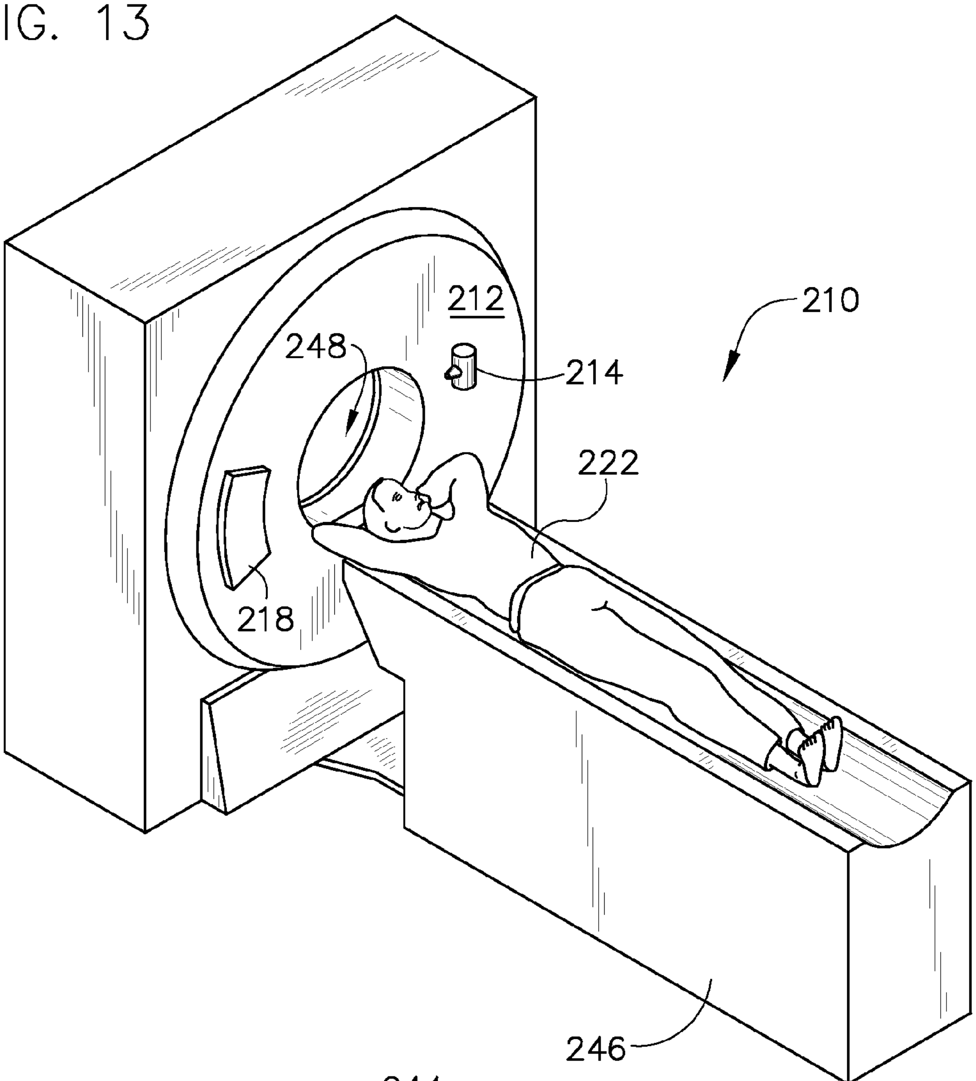


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FIG. 14

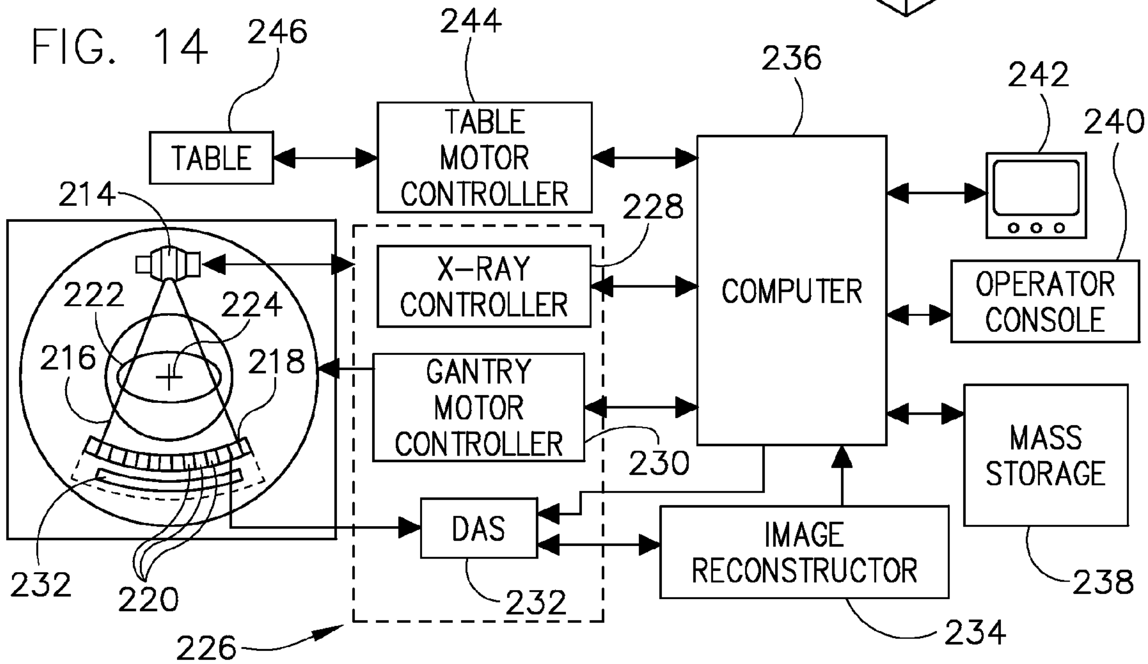

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TABLE MOTOR CONTROLLER
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COMPUTER
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OPERATOR CONSOLE
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X-RAY CONTROLLER
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GANTRY MOTOR CONTROLLER
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MASS STORAGE
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IMAGE RECONSTRUCTOR
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APPARATUS FOR MODIFYING ELECTRON BEAM ASPECT RATIO FOR X-RAY GENERATION

BACKGROUND OF THE INVENTION

The present invention relates generally to electron emitters, and, more particularly, to an apparatus for modifying an aspect ratio of an electron beam to form a focal spot having a desired size and aspect ratio on a target anode.

In an x-ray imaging system, formation of a small focal spot on a target anode is desired to achieve high-quality x-ray imaging. In order to maximize the target thermal management and cathode emission capability, an x-ray tube is configured such that a non-circular (i.e., linear) focal spot is formed on the target. In the imaging system, the detector will view the x-ray spot at a shallow angle (7-12 degree) to achieve an effective small optical spot size.

To achieve a linear focal spot, today's x-ray tubes use a linear electron emitter element or cathode that has almost the same aspect ratio as the desired focal spot, and a focusing cup/electrode is used to focus the electron beam onto the target anode. The drawback of using such large aspect ratio cathodes is its difficulty of beam optics design. That is, with the generation of an electron beam with a large aspect ratio (by a similarly shaped cathode), it is very difficult to design good beam optics, which are required to achieve a small focal spot on the target.

Additionally, with specific reference to x-ray tubes that implement a thermionic cathode, the large aspect ratio of the cathode imposes additional problems. That is, in order for the thermionic cathode to have a uniform emission, the temperature on the cathode surface has to be uniform. In an x-ray tube environment, a temperature of the cathode surface can be as high as 2600 degrees Celsius, while the surrounding area is at room temperature. For a large aspect ratio thermionic cathode, there is a larger edge area, which results in a temperature of the cathode that tends to be less uniform than a circular cathode.

While the use of linear emitter elements that generate linear electron beams has various drawbacks as set forth above, circular emitter elements that generate circular electron beams can mitigate some of these problems. That is, the use of a circular electron beam allows for the simpler design of beam optics that will generate a small focal spot. Additionally, for emitter elements that are in the form of a thermionic cathode, a circular emitter element profile promotes a stable and consistent temperature thereacross, so as to provide for a more uniform emission of electrons.

Thus, a need exists for an apparatus that provides for the generation of a circular electron beam, so as to allow for the simpler design of beam optics for focusing the electron beam, while still providing for formation of a small, linear focal spot on a target anode.

BRIEF DESCRIPTION OF THE INVENTION

Embodiments of the invention overcome the aforementioned drawbacks by providing an apparatus that provides for modifying an aspect ratio of an electron beam to form a focal spot having a desired size and aspect ratio on a target anode.

According to one aspect of the invention, an electron generator unit includes an emitter element configured to generate an electron beam having a first aspect ratio shape and an extraction electrode positioned adjacent to the emitter element to extract the electron beam out therefrom, the extraction electrode including an opening therethrough. The electron generator unit also includes at least one shaping electrode positioned to receive the electron beam after passing through the extraction electrode, the shaping electrode defining a non-circular aperture therein and being configured to provide at least one of shaping and focusing of the electron beam to have a second aspect ratio shape different from the first aspect ratio shape so as to form a focal spot having a desired size and aspect ratio on a target anode.

According to another aspect of the invention, an x-ray tube includes a housing enclosing a vacuum chamber and an electron generator unit positioned within the housing, with the electron generator unit further including an emitter element configured to generate an electron beam having a first aspect ratio, an extraction electrode having an opening therethrough that is positioned adjacent to the emitter element to extract the electron beam out therefrom, and at least one shaping electrode positioned to receive the electron beam after passing through the extraction electrode, with the shaping electrode defining a non-circular opening therein and being configured to shape the electron beam to have a second aspect ratio different from the first aspect ratio. The x-ray tube also includes a target anode positioned in a path of the shaped electron beam and configured to emit high-frequency electromagnetic energy when the shaped electron beam impinges thereon.

According to yet another aspect of the invention, an x-ray tube includes a circular emitter element configured to generate an electron beam having a circular cross-section and a shaping electrode positioned to receive the electron beam from the circular emitter element and having a non-circular aperture formed therethrough, the non-circular aperture of the shaping electrode configured to focus and shape the electron beam as it passes through the shaping electrode such that a shape of the electron beam is modified to have a non-circular cross-section. The x-ray tube also includes a target anode positioned in a path of the non-circular electron beam that is configured to emit high-frequency electromagnetic energy when the non-circular electron beam impinges thereon.

These and other advantages and features will be more readily understood from the following detailed description of preferred embodiments of the invention that is provided in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings illustrate embodiments presently contemplated for carrying out the invention.

In the drawings:

FIG. **1** is a cross-sectional view of an electron emitter unit and target anode in accordance with an embodiment of the present invention.

FIG. **2** is a top plan view of an emitter element and extraction electron for use in the electron emitter unit of FIG. **1** in accordance with an embodiment of the present invention.

FIG. **3** is a perspective view of a shaping electrode for use in the electron emitter unit of FIG. **1** in accordance with an embodiment of the present invention.

FIG. **4** is a perspective view of a shaping electrode for use in the electron emitter unit of FIG. **1** in accordance with an embodiment of the present invention.

FIG. **5** is a perspective view of a shaping electrode for use in the electron emitter unit of FIG. **1** in accordance with an embodiment of the present invention.

FIG. **6** is a cross-sectional view of a shaping electrode for use in the electron emitter unit of FIG. **1** in accordance with an embodiment of the present invention.

FIG. **7** is a cross-sectional view of an electron beam generated by the circular emitter element of FIG. **2**.

FIG. **8** is a cross-sectional view of an electron beam after reshaping by the shaping electrode.

FIG. **9** is a partial cross-sectional view of a field emitter element for use with the electron emitter unit of FIG. **1** in accordance with an embodiment of the present invention.

FIG. **10** is a cross-sectional view of an electron generator unit and target anode in accordance with another embodiment of the present invention.

FIGS. **11** and **12** are schematic views of an x-ray tube according to embodiments of the present invention.

FIG. **13** is a perspective view of a CT imaging system incorporating an embodiment of the present invention.

FIG. **14** is a schematic block diagram of the system illustrated in FIG. **13**.

DETAILED DESCRIPTION OF THE INVENTION

The operating environment of embodiments of the invention is described with respect to an electron generator unit and x-ray source that includes a field emitter based cathode. That is, the electron beam emission and electron beam focusing and reshaping schemes of the invention are described as being provided for an electron generator unit and field emitter based x-ray source. However, it will be appreciated by those skilled in the art that embodiments of the invention for such electron beam emission and electron beam focusing and reshaping schemes are equally applicable for use with other cathode technologies, such as dispenser cathodes and other thermionic cathodes. The invention will be described with respect to a field emitter unit, but is equally applicable with other cold cathode and/or thermionic cathode structures.

Referring to FIG. **1**, a cross-sectional view of an electron generator unit **10** (i.e., cathode assembly) is depicted according to one embodiment of the invention. As will be explained in greater detail below, in one embodiment, electron generator unit **10** is a cold cathode, carbon nanotube (CNT) field emitter unit. However, it is understood that the features and adaptations described herein are also applicable to other types of field emitters, such as Spindt-type emitters, or other thermionic cathode or dispenser cathode type electron generators. As shown in FIG. **1**, electron generator unit **10** includes a substrate layer **12** that is preferably formed of a conductive or semiconductive material such as a doped silicon-based substance or of copper or stainless steel. Therefore, substrate layer **12** is preferably rigid. A dielectric film **14** is formed or deposited over substrate **12** to separate an insulating layer **16** (i.e., ceramic spacer) therefrom. Dielectric film **14** is preferably formed of a non-conductive substance or a substance of a very high electrical resistance, such as silicon dioxide (SiO_2) or silicon nitride (Si_3N_4), or some other material having similar dielectric properties. A channel or aperture **18** is formed in dielectric film **14** by any of several known chemical or etching manufacturing processes.

As shown in FIG. **1**, substrate layer **12** is registered onto insulating layer **16**, which in one embodiment is a ceramic spacer element having desired insulating properties as well as compressive properties for absorbing loads caused by translation of the field emitter unit (e.g., when the field emitter unit forms part of an x-ray source that rotates about a CT gantry). Insulating layer **16** is used to separate the substrate layer **12** from an extraction electrode **20** (i.e., gate electrode, gate layer), so that an electrical potential may be applied between extraction electrode **20** and substrate **12** by way of a voltage supplied by controller **21**. A channel or cavity **22** is formed in insulating layer **16**, and a corresponding opening **24** is formed in extraction electrode **20**. As shown, opening **24** substantially overlaps cavity **22**. In other embodiments, cavity **22** and opening **24** may be of approximately the same diameter, or cavity **22** may be narrower than opening **24** of extraction electrode **20**.

An electron emitter element **26** (i.e., cathode element) is disposed in cavity **22** and affixed on substrate layer **12**. The interaction of an electrical field in opening **22** (created by extraction electrode **20**) with the emitter element **26** generates an electron beam **28** that may be used for a variety of functions when a control voltage is applied to emitter element **26** by way of substrate **12**. In one embodiment, emitter element **26** is a carbon nanotube-based emitter; however, it is contemplated that the emitter element may be in the form of a dispenser cathode or other thermionic cathode.

As shown in FIG. **2**, according to one embodiment of the invention, emitter element **26** is constructed as a circular emitter element (i.e., having a circular cross-section) configured to generate/emit an electron beam or stream of electrons having a circular cross-section or profile (i.e., a first/original beam profile). Similarly, opening **24** of extraction electrode **20** is formed as a circular opening comparable in size to emitter element **26**. Construction of emitter element **26** as a circular element provides for a number of benefits with respect to beam emission and beam focusing. For example, the beam optics design of electron beams having a circular cross-section provides for efficient formation of a small focal spot on a target anode by electron generator unit **10**. Additionally, for embodiments of the invention where emitter element **26** comprises a thermionic cathode, the circular shape of the emitter element allows for increased uniformity in temperature of the element. That is, it is recognized that in order for the thermionic cathode to have a uniform emission, the temperature on the cathode surface has to be uniform. In an x-ray tube environment, the cathode surface would be as high as 2600 degrees Celsius, while the surrounding area is at room temperature. For a thermionic cathode having a large aspect ratio, there is larger edge area and temperature tends to be less uniform than a circular cathode. Thus, construction of emitter element **26** as a circular element provides for greater control of beam optics and temperature control

Referring again to FIG. **1**, according to an exemplary embodiment of the invention where emitter element **26** is formed as a field emitter element, a meshed grid **32** is positioned between cavity **22** of insulating layer **16** and opening **24** of extraction electrode **20** to reduce the voltage needed to extract electron beam **28** from emitter element **26**. This positions meshed grid **32** in proximity to emitter element **26** to reduce the voltage needed to extract electron beam **28** from emitter element **26**. That is, for efficient extraction, a gap between meshed grid **32** and emitter element **26** is kept within a desired distance (e.g., 0.1 mm to 2 mm) in order to enhance the electric field around emitter element **26** and minimize the total extracting voltage supplied by a controller **21** that is necessary to extract electron beam **28**. Placement of meshed grid **32** over cavity **22** allows for an extraction voltage applied to extraction electrode **20** in the range of approximately 1-3 kV, depending on the distance between meshed grid **32** and emitter element **26**. By reducing the total extracting voltage to such a range, high voltage stability of electron generator unit **10** is improved, and higher emission current in electron beam **28** is made possible. The difference in potential between emitter element **26** and extraction electrode **20** is minimized to reduce high voltage instability in emitter unit **10** and simplify the need for complicated driver/control design therein.

As further shown in FIG. **1**, an emittance compensation electrode (ECE) **34** is also included in electron generator unit

10 and is positioned adjacent to meshed grid **32** on an opposite side from emitter element **26** so as to receive electron beam **28** upon exiting the extraction electrode **20**. The ECE **34** is positioned adjacent to meshed grid **32** and functions to minimize beam emittance growth in electron beam **28** caused by the passing of the beam through the meshed grid **32**. That is, the extent of space and momentum phase space (i.e., emittance) occupied by the electrons of electron beam **28** is controlled and minimized by ECE **34**. The ECE **34** includes an aperture **36** formed therein through which electron beam **28** passes. An electrostatic field is generated across aperture **36** by application of a voltage (i.e., a compression voltage) to ECE **34** by way of a controller **54**. The electrostatic field interacts with electron beam **28** such that electrons in electron beam **28** are confined to a small distance in a transverse direction and have nearly the same momentum (i.e., "compressing" electron beam **28**). Such spatial confinement and uniformity in momentum of the electrons reduces emittance growth in electron beam **28**. The voltage applied to ECE **34** by controller **21** typically ranges from about 4 kV to 20 kV, although it is envisioned that lesser or greater voltages can also be applied. Furthermore, the voltage applied to ECE **34** can be either a constant voltage or can be varied. That is, in one embodiment, a voltage applied to ECE **34** corresponds to an extraction voltage applied to extraction electrode **20** and meshed grid **32** (and to substrate **12**) for extracting electron beam **28** from emitter element **26**. Thus, the voltage applied to ECE **34** can be of an amount such that the electric fields present at both sides of meshed grid **32** are equal to one another, allowing for optimized control of emittance growth in electron beam **28**.

ECE **34** also functions to allow for increased beam current modulation of electron beam **28** in electron generator unit **10**. That is, ECE **34** allows for current density in electron beam **28** to be increased to higher levels without suffering an associated degradation in beam quality. When an extraction voltage applied to meshed grid **32** by controller **21** is changed to modulate electron beam current, the compression voltage applied to ECE **34** can also be changed so as to minimize emittance growth in electron beam **28**. That is, when the current density in electron beam **28** is increased by way of an increased extraction voltage being applied to extraction electrode **20** and meshed grid **32** by controller **21**, the compression voltage applied to ECE **34** is also increased so as to allow for greater compression of electron beam **28** and to minimize emittance growth therein. By associating the voltage supplied to extraction electrode **20** and meshed grid **32** with the voltage supplied to ECE **34**, beam quality can always be preserved at different beam current densities. It is also envisioned, however, that rather than varying a voltage applied to ECE **34**, it is also possible that the voltage applied to ECE **34** be fixed relative to the varied voltage applied to extraction electrode **20** and meshed grid **32**. Applying such a fixed voltage to ECE **34** allows for a slight change of the electron beam emittance, the amount of which can be controlled by an operator to a desired value.

As further shown in FIG. **1**, a shaping electrode **38** is included in field electron generator unit **10** and is positioned downstream from ECE **34** to focus and re-shape the electron beam as it passes through an aperture **40** formed therein. According to an exemplary embodiment, shaping electrode **38** is separated from ECE **34** by a spacer element **42** to provide a distance therebetween (e.g., 5-15 mm) that allows for optimized focusing of electron beam **28**. The shaping electrode **38** is energized by a voltage controller **44** that is separate from the controllers that energize the ECE **34** and extraction electrode **20** (i.e., controllers **21**, **54**). In operation, when voltage is provided to shaping electrode **38** from controller **44**, an electrostatic field is generated across aperture **40**. The electrostatic field interacts with electron beam **28** such that electrons in electron beam **28** are focused and a cross-section of the electron beam is reshaped. According to an exemplary embodiment, the amount of voltage applied to the shaping electrode **38** is controlled by controller **44** so as to vary a strength of the electrostatic field, thereby controlling the focusing and reshaping of the electron beam **28**.

The electron beam **28** is focused/reshaped by the electrostatic force generated by shaping electrode **38** such that the electron beam **28** forms a desired focal spot **46** (i.e., a focal spot having a desired aspect ratio) on a target anode **48** that positioned inside a vacuum chamber **47** along with electron generator unit **10** formed by a housing or envelope **49**. As shown in FIG. **1**, target anode **48** is in the form of a tilted, stationary target that is surrounded by a target shield **50**. The target shield **50** provides for capture of secondary electron beams and ions generated from the target anode **48** when the primary electron beam impinges thereon, as well as provides improved high voltage stability. According to an exemplary embodiment, the target anode **48** is tilted by around 7-70 degrees with respect to electron beam **28**. Impinging of electrons on anode target **48** generates x-rays that exit from a viewing window **52** behind the target anode **48**. A detector (not shown) views the x-ray from a shallow angle (7 degree) with respect to the surface of the target anode **48**. While target anode **48** is shown as a tilted, stationary target, it is recognized that the target anode could also be in the form of a rotating target for high power applications.

According to embodiments of the invention, the aperture **40** formed through shaping electrode **38** is non-circular in shape. The non-circular aperture **40** in shaping electrode **38** acts to reshape the circular electron beam as it passes therethrough, so as to form a non-circular electron beam having a desired aspect ratio and provide for formation of a non-circular focal spot **46** (i.e., linear focal spot) on target anode **48**. As shown in FIGS. **3** and **4**, aperture **40** can be any of a variety of non-circular shapes, so as to focus and shape electron beam **28** to have a desired aspect ratio. For example, aperture **40** can be in the form of a rectangular (FIG. **3**) or elliptical (FIG. **4**) shape. As further shown in each of FIGS. **3** and **4**, the aperture **40** is formed as a conical opening to provide further improved focusing of electron beam **28**. That is, shaping electrode **38** is formed to have an angled surface that extends outward and upward from aperture **40**. As shown in FIG. **3**, shaping electrode **38** is angled outward and upward from rectangular aperture **40** in four separate directions, with the portions of the shaping electrode **38** surrounding the rectangular aperture **40** having identical slopes or varying slopes. As shown in FIG. **4**, shaping electrode **38** is angled outward and upward from elliptical aperture **40** in a smooth transition between the aperture and a perimeter of the shaping electrode.

Referring now to FIG. **5**, according to another embodiment of the invention, shaping electrode **38** is constructed to have a multi-piece construction and is formed of four electrode pieces **53**. The four electrode pieces **53** are shaped and arranged so as to define a rectangular shaped aperture **40** (i.e., non-circular aperture) that provides for reshaping of the circular electron beam as it passes therethrough, so as to form a non-circular electron beam having a desired aspect ratio and provide for formation of a non-circular focal spot **46** (i.e., linear focal spot) on target anode **48** (FIG. **1**). Additionally, by supplying varied voltages to electrode pieces **53** (e.g., from controller **44**), shaping electrode **38** can act to deflect electron beam **28** a desired amount, thereby providing for wobbling of the electron beam, as might be desired for use with a rotating target anode.

Referring now to FIG. **6**, according to another embodiment of the invention, shaping electrode **38** is constructed to have an electrostatic quadrupole construction formed of four electrode members **55**. The four electrode members are arranged to have alternating polarities and are positioned so as to generally define a rectangular shaped aperture **40** (i.e., non-circular aperture) that provides for reshaping of the circular electron beam as it passes therethrough, so as to form a non-circular electron beam having a desired aspect ratio and provide for formation of a non-circular focal spot **46** (i.e., linear focal spot) on target anode **48** (FIG. **1**). It is also recognized that a dipole voltage can be added onto electrode members **55** to deflect the electron beam **28** in desired directions.

While electron generator unit **10** is shown and described in FIGS. **1** and **2** as including a circular emitter element **26** that emits an electron beam **28** having a circular profile, it is recognized that the electron generator unit **10** can instead include an emitter element **26** that is non-circular in shape (i.e., a non-circular aspect ratio). That is, according to additional embodiments of the invention, focusing electrode **38** (such as shown in FIGS. **3**-**6**) can shape and focus an electron beam **28** emitted from a non-circular emitter element **26** that has a first aspect ratio (non-circular or circular) such that the beam is modified from a first aspect ratio to a second aspect ratio that is different from the first aspect ratio, and such that a second aspect ratio focal spot **46** can be formed on target anode **48** having a desired size and shape. Thus, embodiments of the invention are not meant to be limited to an electron generator unit **10** having a circular emitter element **26**, but include electron generator units incorporating an emitter element having any aspect ratio shape and employ a shaping electrode with a non-circular aperture to reshape/focus the electron beam to another desired aspect ratio shape.

Referring now to FIGS. **7** and **8**, profiles of the electron beam **28** prior and subsequent to focusing and reshaping by shaping electrode **38** are shown according to an embodiment of the invention. As shown in FIG. **7**, electron beam **28** has a circular profile/cross-section. According to an exemplary embodiment of the invention, the electron beam **28** maintains a circular profile up until it passes through aperture **40** of shaping electrode **38**, such as those shown in FIGS. **3**-**6**. That is, electron beam **28** is generated to have a circular profile by circular emitter element **26**, passes through a circular opening **24** of extraction electrode **20**, and passes through a circular opening **36** of ECE **34**, such that the circular profile of the electron beam **28** is maintained (as shown in FIGS. **1** and **2**). As shown in FIG. **8**, electron beam **28** is reshaped to have a non-circular or "linear" profile. The non-circular profile of aperture **40** formed through shaping electrode **38**, such as those shown in FIGS. **3**-**6**, and the electrostatic filed generated across the aperture **40**, act to focus the electron beam **28** and reshape it from a circular profile to a non-circular profile, such that a focal spot **46** (FIG. **1**) having a desired size and aspect ratio is formed on target anode **48** (FIG. **1**).

Referring now to FIG. **9**, according to an exemplary embodiment, emitter element **26** is formed of a plurality of carbon nanotubes (CNTs) **54**, which are arranged to form an emitter element having a circular profile (such as shown in FIG. **2**). To reduce the attenuation of electron beam **28** caused by the striking of electrons against meshed grid **32**, CNTs **54** are patterned into multiple CNT groups **56** that are aligned with openings **58** in the grid. By aligning CNT groups **56** with openings **58** in meshed grid **32**, interception of beam current in electron beam **28** can be reduced to almost zero, depending on the grid structures. Also, by aligning CNT groups **56** with openings **58**, a substantially higher fraction of electrons will pass through the grid **32**, thus increasing the total beam emission current and allowing for optimal focusing of electron beam **28** for forming a desired focal spot.

As further shown in FIG. **9**, electron beam **28** is generated to maintain a circular profile as it passes through meshed grid **32** positioned in aperture **24** of extraction electrode **20** and as it passes through aperture **36** of ECE **34**. Upon reaching shaping electrode **38**, electron beam **28** is caused to pass through non-circular aperture **40** of the shaping electrode **38** and is acted upon by the electrostatic filed generated across the non-circular aperture. Electron beam **28** is focused and reshaped by shaping electrode **38** such that it exits the shaping electrode **38** having a non-circular profile that will form a linear focal spot **46** on target anode **48** (FIG. **1**) having a desired aspect ratio.

Referring now to FIG. **10**, a cross-sectional view of an electron generator unit **60** is depicted according to another embodiment of the invention. Electron generator unit **60** has a structure identical to that of electron generator unit **10** shown in FIG. **1**, but additionally includes therein one or more magnetic quadrupole members and/or one or more magnetic dipole members **62** configured to provide additional electron beam focusing, shaping, and/or deflection (e.g., for wobbling of the electron beam). As shown in FIG. **7**, a single magnetic quadrupole member **62** is included in electron generator unit **60**, although it is recognized that a greater number of magnetic quadrupole and dipole members could be implemented, such as three for example. Quadrupole and/or dipole member **62** is positioned outside of vacuum chamber **47** defined by housing **49** and is positioned downstream of the shaping electrode **38** such that, upon focusing/reshaping of electron beam **28** provided by shaping electrode **38**, additional focusing, shaping, and/or deflection of the electron beam can be applied by magnetic quadrupole member **62** to modify the non-circular electron beam **28** output from shaping electrode **38** such that it has a desired size and aspect ratio and position.

Referring now to FIGS. **11** and **12**, an x-ray generating tube **140**, such as for use with a CT system, is shown according to embodiments of the invention. Principally, x-ray tube **140** includes a cathode assembly **142** and an anode assembly **144** encased in a housing **146**, with cathode assembly **142** being constructed in accordance with the electron generator unit **10** shown and described in FIG. **1**, and specifically including a shaping electrode **38** having a non-circular aperture (FIGS. **3**-**6**). As shown in FIGS. **11** and **12**, anode assembly **144** includes a rotor **158** configured to turn a rotating anode disc **154**, and an anode shield **156** surrounding the anode disc, as is known in the art. When struck by an electron current **162** from cathode assembly **142**, anode **156** emits an x-ray beam **160** therefrom. Cathode assembly **142** incorporates an electron source **148** positioned in place by a support structure **150**. According to an exemplary embodiment, electron source **148** is in the form of a CNT FE unit that produces the primary electron current **162**. According to the embodiment of FIG. **11**, housing **146** of x-ray tube **140** is formed having a generally uniform circumference along an entire length thereof and defining a vacuum about cathode assembly **142** and anode **156**. According to the embodiment of FIG. **12**, housing **146** of x-ray tube **140** is formed to include a neck **164** between cathode assembly **142** and anode **156** through which electron current **162** passes, such that one or more magnetic quadrupole or dipole members **166** can be implemented outside the housing **146** to shape, focus and deflect electron current **162**.

Referring to FIG. **13**, a computed tomography (CT) imaging system **210** is shown as including a gantry **212** representative of a "third generation" CT scanner. Gantry **212** has an x-ray source **214** that rotates thereabout and that projects a beam of x-rays **216** toward a detector assembly or collimator **218** on the opposite side of the gantry **212**. X-ray source **214** includes an x-ray tube having an electron generator constructed as in accordance with that shown in FIGS. **1**-**6**. Referring now to FIG. **14**, detector assembly **218** is formed by a plurality of detectors **220** and data acquisition systems (DAS) **232**. The plurality of detectors **220** sense the projected x-rays that pass through a medical patient **222**, and DAS **232** converts the data to digital signals for subsequent processing. Each detector **220** produces an analog electrical signal that represents the intensity of an impinging x-ray beam and hence the attenuated beam as it passes through the patient **222**. During a scan to acquire x-ray projection data, gantry **212** and the components mounted thereon rotate about a center of rotation **224**.

Rotation of gantry **212** and the operation of x-ray source **214** are governed by a control mechanism **226** of CT system **210**. Control mechanism **226** includes an x-ray controller **228** that provides power, control, and timing signals to x-ray source **214** and a gantry motor controller **230** that controls the rotational speed and position of gantry **12**. X-ray controller **228** is preferably programmed to account for the electron beam amplification properties of an x-ray tube of the invention when determining a voltage to apply to field emitter based x-ray source **214** to produce a desired x-ray beam intensity and timing. An image reconstructor **234** receives sampled and digitized x-ray data from DAS **232** and performs high speed reconstruction. The reconstructed image is applied as an input to a computer **236** which stores the image in a mass storage device **238**.

Computer **236** also receives commands and scanning parameters from an operator via console **240** that has some form of operator interface, such as a keyboard, mouse, voice activated controller, or any other suitable input apparatus. An associated display **242** allows the operator to observe the reconstructed image and other data from computer **236**. The operator supplied commands and parameters are used by computer **236** to provide control signals and information to DAS **232**, x-ray controller **228** and gantry motor controller **230**. In addition, computer **236** operates a table motor controller **244** which controls a motorized table **246** to position patient **222** and gantry **212**. Particularly, table **246** moves patients **222** through a gantry opening **248** of FIG. **13** in whole or in part.

While described with respect to a sixty-four-slice "third generation" computed tomography (CT) system, it will be appreciated by those skilled in the art that embodiments of the invention are equally applicable for use with other imaging modalities, such as electron gun based systems, x-ray projection imaging, package inspection systems, as well as other multi-slice CT configurations or systems or inverse geometry CT (IGCT) systems. Moreover, the invention has been described with respect to the generation, detection and/or conversion of x-rays. However, one skilled in the art will further appreciate that the invention is also applicable for the generation, detection, and/or conversion of other high frequency electromagnetic energy.

Therefore, according to one embodiment of the invention, an electron generator unit includes an emitter element configured to generate an electron beam having a first aspect ratio shape and an extraction electrode positioned adjacent to the emitter element to extract the electron beam out therefrom, the extraction electrode including an opening therethrough. The electron generator unit also includes at least one shaping electrode positioned to receive the electron beam after passing through the extraction electrode, the shaping electrode defining a non-circular aperture therein and being configured to provide at least one of shaping and focusing of the electron beam to have a second aspect ratio shape different from the first aspect ratio shape so as to form a focal spot having a desired size and aspect ratio on a target anode.

According to another embodiment of the invention, an x-ray tube includes a housing enclosing a vacuum chamber and an electron generator unit positioned within the housing, with the electron generator unit further including an emitter element configured to generate an electron beam having a first aspect ratio, an extraction electrode having an opening therethrough that is positioned adjacent to the emitter element to extract the electron beam out therefrom, and at least one shaping electrode positioned to receive the electron beam after passing through the extraction electrode, with the shaping electrode defining a non-circular opening therein and being configured to shape the electron beam to have a second aspect ratio different from the first aspect ratio. The x-ray tube also includes a target anode positioned in a path of the shaped electron beam and configured to emit high-frequency electromagnetic energy when the shaped electron beam impinges thereon.

According to yet another embodiment of the invention, an x-ray tube includes a circular emitter element configured to generate an electron beam having a circular cross-section and a shaping electrode positioned to receive the electron beam from the circular emitter element and having a non-circular aperture formed therethrough, the non-circular aperture of the shaping electrode configured to focus and shape the electron beam as it passes through the shaping electrode such that a shape of the electron beam is modified to have a non-circular cross-section. The x-ray tube also includes a target anode positioned in a path of the non-circular electron beam that is configured to emit high-frequency electromagnetic energy when the non-circular electron beam impinges thereon.

While the invention has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the invention is not limited to such disclosed embodiments. Rather, the invention can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the invention. Additionally, while various embodiments of the invention have been described, it is to be understood that aspects of the invention may include only some of the described embodiments. Accordingly, the invention is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

What is claimed is:

1. An electron generator unit comprising:

an emitter element configured to generate an electron beam having a first aspect ratio shape;

an extraction electrode positioned adjacent to the emitter element to extract the electron beam out therefrom, the extraction electrode including an opening therethrough in which a meshed grid is positioned;

at least one shaping electrode positioned to receive the electron beam after passing through the extraction electrode, the shaping electrode defining a non-circular aperture therein and being configured to provide at least one of shaping and focusing of the electron beam to have a second aspect ratio shape different from the first aspect ratio shape so as to form a focal spot having a desired size and aspect ratio on a target anode;

an emittance compensation electrode (ECE) positioned between the extraction electrode and the shaping electrode and configured to control emittance growth of the electron beam, such that electrons in the electron beam are compressed along a direction of travel of the electron beam and caused to have nearly the same momentum; and

a controller configured to:

cause a voltage to be applied to the extraction electrode to generate a desired current density in the electron beam;

determine a voltage to be applied to the ECE that minimizes emittance growth of the electron beam based on the voltage applied to the extraction electrode; and

cause the determined voltage to be applied to the ECE such that electric fields present at opposing sides of the meshed grid are equal;

wherein, in applying the determined voltage to the ECE, the spread of electrons in the electron beam along the direction of travel of the electron beam is controlled so as to minimize emittance growth.

2. The electron generator unit of claim **1** wherein the at least one shaping electrode comprising a unitary structure, and wherein the non-circular aperture comprises an angled opening formed in the unitary structure.

3. The electron generator unit of claim **2** wherein the non-circular aperture comprises an elliptical aperture.

4. The electron generator unit of claim **2** wherein the non-circular aperture comprises a rectangular aperture.

5. The electron generator unit of claim **1** wherein the meshed grid reduces a voltage needed to extract the electron beam from the emitter element, the meshed grid having a plurality of openings therein.

6. The electron generator unit of claim **5** wherein the emitter element comprises a carbon nano-tube (CNT) field emitter including a plurality of CNT groups, and wherein each of the plurality of CNT groups is aligned with a respective opening in the meshed grid.

7. The electron generator unit of claim **1** wherein the emitter element comprises a circular emitter element configured to generate a circular electron beam; and

wherein the at least one shaping electrode is configured to reshape the circular electron beam into a non-circular electron beam.

8. The electron generator unit of claim **1** wherein the controller is further configured to control a voltage applied to the at least one shaping electrode to vary a strength of the electrostatic field, thereby controlling the focusing and reshaping of the electron beam.

9. The electron generator unit of claim **8** wherein the at least one shaping electrode comprises a multi-piece electrode constructed to define the non-circular aperture, and wherein each piece of the multi-piece electrode receives an individually controllable voltage from the controller.

10. The electron generator unit of claim **1** wherein the emitter element comprises a one of a carbon nano-tube (CNT) field emitter and a thermionic cathode.

11. The electron generator unit of claim **1** further comprising at least one of a magnetic quadrupole member and a magnetic dipole member positioned to receive the electron beam after passing through the at least one shaping electrode, the at least one of the magnetic quadrupole member and the magnetic dipole member configured to provide at least one of focusing, shaping, and deflection of the electron beam to form a non-circular focal spot on the target anode having a desired size, aspect ratio, and position.

12. An x-ray tube comprising:

a housing enclosing a vacuum chamber;

an electron generator unit positioned within the housing, the electron generator unit comprising:

an emitter element configured to generate an electron beam having a first aspect ratio;

an extraction electrode positioned adjacent to the emitter element to extract the electron beam out therefrom, the extraction electrode including an opening therethrough in which a meshed grid is positioned;

an emittance compensation electrode (ECE) positioned downstream from the extraction element and configured to compress the electron beam in space and momentum phase space; and

at least one shaping electrode positioned to receive the electron beam after passing through the extraction electrode, the shaping electrode defining a non-circular opening therein and being configured to shape the electron beam to have a second aspect ratio different from the first aspect ratio; and

a target anode positioned in a path of the shaped electron beam and configured to emit high-frequency electromagnetic energy when the shaped electron beam impinges thereon; and

a controller configured to:

cause a voltage to be applied to the extraction electrode to generate a desired current density in the electron beam;

determine a voltage to be applied to the ECE that minimizes emittance growth of the electron beam based on the voltage applied to the extraction electrode; and

cause the determined voltage to be applied to the ECE such that electric fields present at opposing sides of the meshed grid are equal;

wherein, in applying the determined voltage to the ECE, the spread of electrons in the electron beam along the direction of travel of the electron beam is controlled so as to minimize emittance growth.

13. The x-ray tube of claim **12** wherein the non-circular opening formed through the focusing element comprises an angled opening having one of an elliptical shape and a rectangular shape.

14. The x-ray tube of claim **12** wherein the controller is further configured to supply a controlled voltage to the shaping electrode, thereby causing the shaping electrode to generate an electrostatic field.

15. The x-ray tube of claim **14** wherein the shaping electrode is configured to focus and shape the circular stream of electrons to form a linear focal spot on a target anode without bending the stream of electrons.

16. An x-ray tube comprising:

a circular emitter element configured to generate an electron beam having a circular cross-section;

an extraction electrode positioned adjacent to the emitter element to extract the electron beam out therefrom, the extraction electrode including an opening therethrough that includes a meshed grid positioned therein to reduce a voltage needed to extract the electron beam from the emitter element, with the meshed grid having a plurality of openings therein;

a shaping electrode positioned to receive the electron beam from the circular emitter element and having a non-circular aperture formed therethrough, the non-circular aperture of the shaping electrode configured to focus and shape the electron beam as it passes through the shaping electrode such that a shape of the electron beam is modified to have a non-circular cross-section;

an emittance compensation electrode (ECE) positioned between the circular emitter element and the shaping electrode and configured to control electron beam emittance growth by compressing electrons in the beam along the direction of travel of the electron beam;

a target anode positioned in a path of the non-circular electron beam and being configured to emit high-frequency electromagnetic energy when the non-circular electron beam impinges thereon; and

a controller configured to apply a variable voltage to the shaping electrode to generate an electrostatic force to control focusing and shaping of the electron beam;

wherein the controller is further configured to:

cause a voltage to be applied to the extraction electrode to generate a desired current density in the electron beam;

determine a voltage to be applied to the ECE that minimizes emittance growth of the electron beam based on the voltage applied to the extraction electrode; and

cause the determined voltage to be applied to the ECE such that electric fields present at opposing sides of the meshed grid are equal;

wherein, in applying the determined voltage to the ECE, the spread of electrons in the electron beam along the direction of travel of the electron beam is controlled so as to minimize emittance growth

wherein the shaping electrode comprises a plurality of electrode pieces arranged to define the non-circular aperture, and wherein each of the plurality of electrode pieces receives an individually variable voltage from the controller in order to focus and shape the electron beam as it passes through the non-circular aperture.

17. The x-ray tube of claim **16** wherein the shaping electrode is configured to focus and shape the electron beam to have a non-circular cross-section so as to form a linear focal spot on the target anode having a desired aspect ratio.

18. The x-ray tube of claim **16** wherein the non-circular aperture formed through the shaping electrode comprises one of an elliptical aperture and a rectangular aperture.

19. The x-ray tube of claim **16** further comprising at least one of a magnetic quadrupole member and a dipole member positioned to receive the electron beam after passing through the shaping electrode, the at least one of the quadrupole member and the dipole member configured to further focus, shape, or deflect the electron beam to form a focal spot on the target anode having a desired size and aspect ratio.

20. The x-ray tube of claim **16** wherein the shaping electrode comprises a plurality of electrode pieces arranged to define the non-circular aperture, and wherein each of the plurality of electrode pieces receives an individually variable voltage from the controller in order to focus and shape the electron beam as it passes through the non-circular aperture.

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