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(54) **Miniature X-ray source with guiding means for electrons and / or ions**

(57) The invention relates to a miniature X-ray source comprising a vacuum tube containing a cathode and an anode spaced apart from each other, and guiding means for guiding electrons and/or ions to prevent the electrons and/or ions from impacting at least a part of a wall of the vacuum tube, e.g. at the wall of the vacuum tube in a region of the vacuum tube where, in use, an electric field is present.

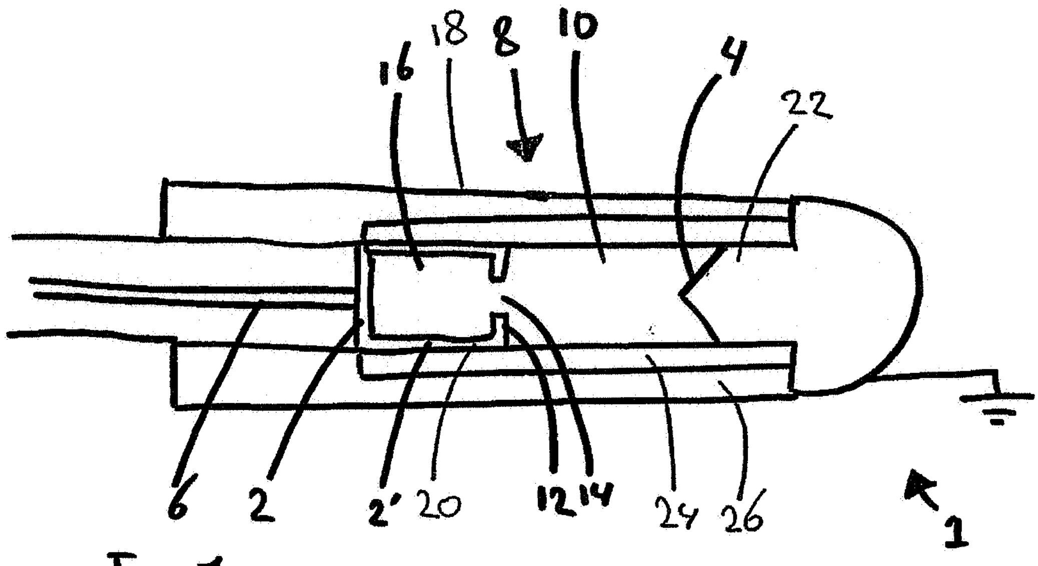

Fig. 1a

EP 2 006 880 A1

Description

[0001] The invention relates to a miniature X-ray source comprising a vacuum tube containing a cathode and an anode spaced apart from each other.

[0002] X-ray sources are known per se. The sources are used for generating X-ray radiation by applying an electrical potential difference between the cathode and the anode so that electrons, emitted by the cathode are accelerated towards the anode. The accelerated electrons impact at the anode causing X-ray radiation to be emitted if the energy of the impacting electron is high enough. Typically, electron energies of 10 - 50 keV (requiring a potential difference or acceleration voltage of 10-50 kV) are desired for generating X-ray radiation with photon energies of 10- 50 keV, e.g. for use in (medical) imaging, inspection, detection, material analysis (diffraction, fluorescence, Auger), lithography (e.g. LIGA, e.g. for MEMS devices), sterilisation and medical treatments. Miniature X-ray sources, i.e. with typical dimensions on the order of millimetres, e.g. smaller than 10 mm, are also known. These known miniature X-ray devices, e.g. for medical application, can only be operated at low acceleration voltages, e.g. up to 20 kV. To generate high energy X-ray radiation, i.e. radiation with X-ray photon energy higher than 20 keV, high acceleration voltages are needed, i.e. voltages higher than 20kV. The reduced size of the miniature X-ray device, however, results in local high electrical fields strengths initiating destroying electrical breakthroughs.

[0003] The object of the invention is to provide the miniature X-ray source with which it is possible to generate high energy X-ray radiation. Alternatively the object of the invention is to provide the miniature X-ray source with the reduced risk of electrical breakthroughs. Alternatively the object of the invention is to provide further miniaturisation of the X-ray source.

[0004] Thereto, according to a first aspect of the invention, the miniature X-ray source is provided with the guiding means for guiding electrons and/or ions to prevent the electrons and/or ions from impacting at least a part of a wall of the vacuum tube. Preferably, the guiding means are arranged for guiding electrons and/or ions to prevent the electrons and/or ions from impacting the wall of the vacuum tube in a region of the vacuum tube where, in use, an electric field is present.

[0005] It has been found that electrons and/or ions impacted at the wall of the vacuum tube, especially in the region of the vacuum tube where, in use, the electric field is present, are likely to act as an electron source and may therefore function as the origin of electrical breakthrough. Alternatively, electrons and/or ions impacted at the wall of the vacuum tube may electrically charge that wall. This in turn may cause the wall to act as an electrical lens, which upsets the desired path of flight of the electrons from the cathode to the anode.

[0006] The guiding means guide electrons and/or ions away from the wall of the vacuum tube, e.g. in the region of the vacuum tube where, in use, the electric field is present. Hence, the risk of electrons and/or ions impacting the wall of the vacuum tube, e.g. in the region of the vacuum tube where, in use, the electric field is present, is reduced. Thus, by reducing the chance of electrons and/or ions impacting the wall at these locations, the guiding means reduce the risk of electrical breakthrough and/or electrical charging of the wall.

[0007] As the risk of electrical breakthrough is reduced in the miniature X-ray source of the invention, the acceleration voltage between the anode and the cathode may be increased, e.g. until an acceptable level of breakthrough-risk is attained. Thus, it is possible with the miniature X-ray source according to the invention to generate high energy X-ray radiation, e.g. with a photon energy of 30 keV or more, preferably 40 keV or more, most preferably 50 keV or more.

[0008] The guiding means may comprise a directional barrier interposed between the cathode and the anode wherein the barrier is arranged to transmit, in use, electrons emitted by the cathode towards the anode, and wherein the barrier is arranged to, in use, substantially prevents electrons and/or ions to pass the barrier in the direction of the anode towards the cathode.

[0009] Electrons impacting on the anode may, instead of X-ray radiation, also cause electrons or ions to be emitted (or reflected) by the anode. Since the directional barrier substantially prevent electrons and/or ions to pass the barrier in the direction of the anode towards the cathode, substantially none of these electrons and/or ions can impact the cathode or the inner wall of the vacuum tube between the cathode and the directional barrier. The directional barrier, thus, reduces the risk of electrical breakthrough and/or electrical charging of the wall of the vacuum tube.

[0010] In an embodiment the directional barrier is an electrically conducting diaphragm comprising an aperture, wherein the diaphragm is arranged to be maintained at the same electric potential as the anode. Hence, in use, the diaphragm makes that the accelerating electrical field is maintained between the cathode and the diaphragm, and that substantially no electrical field is present between the diaphragm and the anode. Since there is substantially no electrical field between the diaphragm and the anode, electrical breakthrough will not occur between the diaphragm and the anode. Further, as the diaphragm substantially prevents electrons and/or ions to pass the barrier in the direction of the anode towards the cathode, substantially none of these electrons and/or ions can impact the cathode or the inner wall of the vacuum tube between the cathode and the directional barrier, i.e. in the region of the vacuum tube where, in use, the electric field is present.

[0011] Preferably, the anode and the diaphragm together form the, electrically conducting, walls of a chamber which is preferably closed except for the aperture. Thus, a chamber is created in which substantially no electrical field is present. Electrons and/or ions emitted or reflected by the anode are highly likely to strike a wall of the chamber. The risk that such electron or ion exits the chamber through the aperture is very small.

[0012] Alternatively, or additionally, the guiding means may comprise electron focussing means for directing, in use, the electrons emitted by the cathode in a direction towards the anode, such that substantially all electrons emitted by the cathode are prevented from impacting the at least a part of the wall of the vacuum tube. Preferably, the electron focussing means are arranged for directing, in use, the electrons emitted by the cathode in a direction towards the anode, such that substantially all electrons emitted by the cathode are prevented from impacting the wall in the region of the vacuum tube where, in use, the electric field is present. Hence, the electrons emitted by the cathode will follow a path such that they do not impact the inner wall of the vacuum tube between the cathode and the anode, thus reducing the risk of electrical breakthrough.

[0013] Preferably, the electron focussing means direct the electrons emitted by the cathode in a direction such that substantially all electrons emitted by the cathode are transmitted by the directional barrier. Hence, substantially no electrons emitted by the cathode can impact the inner wall of the vacuum tube between the cathode and the directional barrier, the directional barrier itself or the vacuum tube after collision with the directional barrier. Since, electrons impacted at the vacuum tube are likely to act as electron source and may therefore function as the origin of electrical breakthrough, the electron focusing means, thus, reduce the risk of electrical breakthrough.

[0014] The directional barrier allows the electrons emitted by the cathode to be transmitted towards the anode, so that efficiency of the X-ray source is not, at least hardly, adversely affected by the presence of the barrier.

[0015] Preferably, the electron focussing means are arranged for directing substantially all electrons emitted by the cathode through the aperture in the direction of the anode. Hence, substantially all electrons emitted by the cathode pass through the aperture and are effectively caught downstream of the aperture, e.g. in the chamber, so that these electrons cannot cause electrical breakthrough.

[0016] In an embodiment the electron focussing means comprise an electric and/or magnetic lens. Hence it is possible to in a simple manner direct the electrons emitted by the cathode in a direction such that substantially all electrons emitted by the cathode are transmitted by the directional barrier.

[0017] In an embodiment the cathode is concave, in a direction towards the anode, wherein the concave shape acts as the electric lens for directing, in use, the electrons emitted by the cathode in a direction such that substantially all electrons emitted by the cathode are transmitted by the directional barrier.

[0018] In an embodiment in the vacuum tube a grid shaped electron absorbing element is disposed between the cathode and the directional barrier for absorbing any electrons being reflected from the barrier towards the cathode or the wall of the vacuum tube. Thus, even more efficiently electrical breakthrough may be prevented.

[0019] According to a second aspect of the invention the cathode is of a cold cathode type comprising carbon nanotubes for emitting electrons. The use of the cold cathode poses less thermal load to the X-ray source which enables further miniaturisation of the X-ray source.

[0020] Preferably, the carbon nanotubes are aligned mono-wall nanotubes, aligned multi-wall nanotubes, randomised mono-wall nanotubes or randomised multi-wall nanotubes. The nanotubes provide an efficient source of electrons for the cathode of the miniature X-ray source.

[0021] According to a third aspect of the invention, the miniature X-ray source may comprise a tubular housing of an electrically isolating material having an electrically conducting first cap or first plug associated with the anode at a first end and an electrically conducting second cap or second plug associated with the cathode at the other, second end. Hence, a structure is provided which allows easy miniaturisation. The electrically isolating material may for instance be a ceramic material, such as aluminium oxide (alumina) or another material defect free material such as diamond or mono crystalline quartz. A particularly suitable material is optically transparent alumina, which appears to have a high dielectric strength.

[0022] According to a fourth aspect of the invention the vacuum tube, e.g. the tubular housing, is at least partly made of an electrically isolating material. Inside the wall of the vacuum tube an electric field is generated, e.g. adjacent the anode and/or cathode which may be at a potential difference with an outer side of the vacuum tube.

[0023] Preferably, the vacuum tube comprises an inner wall, of a first material and an outer wall of a second material. Preferably, a dielectric constant of the first material is higher than a dielectric constant of the second material, and a dielectric strength of the second material is higher than a dielectric strength of the first material. Herein the dielectric strength is the maximum electric field strength that a material can withstand without electrical breakthrough, i.e. without experiencing failure of its insulating properties. The first material may be a ceramic material, such as aluminium oxide (alumina), and the second material may be a polymeric material, such as polyethylene.

[0024] Preferably, the thickness of the inner wall and the outer wall is such that the electric field strength inside the inner wall is smaller than the electric field strength in the outer wall. It will be appreciated that it is, thus, possible to ensure that by choosing the desired thickness for the inner and outer wall the electric field strength inside the inner wall can be kept smaller than the dielectric strength of the first material, and the electric field strength inside the outer wall can be kept smaller than the dielectric strength of the second material. Hence, it is possible to provide a wall of the vacuum tube comprising the inner and the outer wall, such that the total wall thickness is minimized, while breakthrough across the wall is substantially prevented. Thus, further miniaturisation of the miniature X-ray source may be achieved.

[0025] According to a fifth aspect of the invention, a triple junction may be shielded by an electrically conducting, e.g. metal, layer at the outside surface of the electrically isolating tubular housing.

[0026] When placed in a electrical field, local materials defects and roughness of materials initiate local high electrical field strengths. These locations act as electron source and often function as the origin of electrical breakthrough. In particular, triple junctions of electrical conductor (e.g. metal), electrical insulator and vacuum act as such. A tubular triple junction may be formed where the electrically conducting first and/or second cap or plug, the electrically isolating tubular housing and the vacuum meet. Such tubular triple junction thus poses a risk for electrical breakthrough. Since, according to the fifth aspect of the invention, the tubular triple junction may be shielded by an electrically conducting, e.g. metal, layer at the outside surface of the electrically isolating tubular isolator, which layer may be kept at the same electrical potential as the respective cap or plug, the electrical field inside the electrically isolating tubular housing at or near that triple junction is caused to be more homogeneous, thus reducing the risk of electrical breakthrough.

[0027] According to a sixth aspect of the invention, a high electrical resitivity coating (resistivity in the rang 10^6 -10^{10} ohm·cm may be applied on the inner side and/or outer side of the vacuum tube, e.g. on the electrically isolating tubular housing. The high resistivity coating may be electrically conducting connected to the anode and the cathode, e.g. at the first end of the tubular housing and the second end of the tubular housing, respectively. Thus, the high resistivity coating may enforce a gradual linear voltage distribution along the wall of the vacuum tube, e.g. along the isolating tubular housing (glass or ceramic) as a result of a small electric current (e.g. 0.1 to 100 μA) that may flow through the high resistivity coating.

[0028] Preferably, the high resistivity coating substantially completely covers the vacuum tube between the anode and the cathode. In an embodiment, the high resistivity coating substantially completely covers the tubular housing between a first electrically conducting layer associated with the triple junction associated with the anode and a second electrically conducting layer associated with the triple junction associated with the cathode.

[0029] It will be appreciated that the first, second, third, fourth, fifth and sixth aspect of the invention may be practiced separately or in any combination thereof.

[0030] The invention will now be further elucidated by means of the following, non-limiting, examples and the accompanying drawing in which,

Fig. 1a shows a schematic sectional view of a first embodiment of a miniature X-ray source according to the invention;

Fig. 1b shows a schematic sectional view of a variation of the embodiment according to Fig. 1a;

Fig. 2 shows a graph in which the highest electric field value occurring in a tubular wall comprising an inner wall and an outer wall is demonstrated;

Fig. 3 shows a schematic sectional view of a second embodiment of a miniature X-ray source according to the invention;

Fig. 4 shows a schematic sectional view of a third embodiment of a miniature X-ray source according to the invention; and

Fig. 5 shows a schematic sectional view of an array of miniature X-ray sources according to a fourth embodiment of invention.

[0031] In the figures similar features are indicated with the same reference numerals.

[0032] Fig. 1a shows a schematic sectional view of a first embodiment of a miniature X-ray source 1 according to the invention. The source 1 comprises an anode 2 and a cathode 4. In the example of Fig. 1a the source 1 further comprises a housing in the form of a vacuum tube 8 enclosing an inner space 10 in which a vacuum is present.

[0033] This miniature X-ray source may e.g. be of generally cylindrical design, having a diameter of approximately 1-2.5 mm and a length of less than approximately 3 cm, preferably less than approximately 2 cm.

[0034] In the example of Fig. 1a the miniature X-ray source 1 further comprises a diaphragm 12 comprising an aperture 14. Here the diaphragm is made of an electrically conducting material. In this example the anode 2, a tubular extension 2' of the anode 2, and the diaphragm 12 together form electrically conducting walls of a chamber 16 which is closed except for the aperture 14. It will be appreciated that in this embodiment, the anode 2,2' and the diaphragm 12 may be considered to form an electrically conducting box 2,2',12 with the aperture 14 as entrance for the accelerated electrons.

[0035] The miniature X-ray source explained so far can be operated as follows.

[0036] In this example the cathode 4 is maintained at earth potential (0 V), and the anode is maintained at a high voltage, e.g. 60 kV. In Fig. 1a a power supply line 6 is drawn electrically conducting connected to the anode 2. The cathode 4 may also be supplied with a power supply line. In this example the cathode is directly connected to earth, e.g. through an electrically conducting cooling fluid, such as water. Maintaining the cathode 4, i.e. the electron emitter at earth electric potential helps providing an electrical field inside the X-ray source which is substantially mainly axial and directed towards the anode 2, as the surroundings of the tubular housing 18 are also likely at earth electric potential. It will be appreciated that maintaining the cathode at earth electric potential will also be beneficial in the following examples of Figs. 3, 4 and 5, of tubular miniature X-ray source.

[0037] When the high electrical potential difference is maintained between the cathode 4 and the anode 2, the cathode 4 will emit electrons which, due to the electric field caused by the electric potential difference, will be accelerated towards the anode 2.

[0038] At least a portion of the electrons emitted by the cathode 4 passes through the aperture 14 and impacts on the anode 2. Upon impact X-ray radiation is generated. This X-ray radiation passes through the wall 2' of the box and through the wall of the vacuum tube 8. Thus substantially a point-source of X-ray radiation is obtained.

[0039] Some electrons impacting on the anode may, instead of X-ray radiation, also cause electrons or ions to be emitted (or reflected) by the anode. These electrons and/or ions may travel in the direction of the wall of the vacuum tube or in the general direction of the cathode 4.

[0040] The diaphragm blocks the path of flight of at least a portion of the electrons and/or ions travelling in the general direction of the cathode 4. Hence, these electrons and/or ions will be prevented from impacting the cathode 4 or the inner wall of the vacuum tube 8 between the cathode 4 and the diaphragm 12, where in this case an electric field is present. Hence, these electrons and/or ion will not form electron sources, so that the risk of electrical breakthrough is reduced.

[0041] Thus, the diaphragm 12 forms a directional barrier interposed between the cathode 4 and the anode 2 wherein the barrier is arranged to transmit, in use, electrons emitted by the cathode 4 towards the anode 2, and wherein the barrier is arranged to, in use, substantially prevent electrons and/or ions to pass the barrier in the direction of the anode 2 towards the cathode 4

[0042] The diaphragm 12 at the same electrical potential as the anode 2 also causes that between the anode 2 and the diaphragm 12 no electrical field is present. Thus, electrons and/or ions impacting the wall of the vacuum tube 8 (or the wall 2') between the anode 2 and the diaphragm 12 will not cause electrical breakthrough.

[0043] It will be appreciated that the diaphragm 12 may also be separate from the anode 2, while the diaphragm 12 is maintained at the same electric potential as the anode 2.

[0044] It will be appreciated that the diaphragm 12 thus forms guiding means for guiding electrons and/or ions to prevent the electrons and/or ions from impacting a wall of the vacuum tube 8, in this example in a region of the vacuum tube where, in use, an electric field is present.

[0045] It will be appreciated that if the diaphragm is not electrically conductive it will, nevertheless, prevent at least some electrons and/or ions from impacting a wall of the vacuum tube 8.

[0046] In the example of Fig. 1a the vacuum tube 8 comprises a tubular housing 18. The vacuum tube 8 further has an electrically conducting first plug 20 at a first end and an electrically conducting second plug 22 at the other, second end. Here the first plug 20 is formed by the anode. Here the second plug 22 is formed by the cathode. The first and second plug 20,22 are joined to the tubular housing 18 in a vacuum tight manner, e.g. by laser welding or brazing.

[0047] It will be appreciated that alternatively, the vacuum tube may comprise an electrically conducting first cap, e.g. acting as or being part of the anode, at the first end and an electrically conducting second cap, e.g. acting as or forming part of the cathode, at the second end.

[0048] In this example, the vacuum tube 8, more specifically the tubular housing 18, comprises an inner wall 24, of a first material and an outer wall 26 of a second material. The first and second material are selected such that a dielectric constant of the first material is higher than a dielectric constant of the second material, and that a dielectric strength of the second material is higher than a dielectric strength of the first material. The first material may be a ceramic material, such as aluminium oxide (alumina) or boron nitride or another material defect free material such as glass, diamond or mono crystalline quartz. It is known that optically transparent alumina provides a high dielectric strength. The second material may be a polymeric material, such as polyethylene. In the example of Fig. 1a the inner wall 24 is alumina and the outer wall 26 is polyethylene.

[0049] Preferably, the thickness of the inner wall 24 and the outer wall 26 is such that the electric field strength inside the inner wall 24 is smaller than the electric field strength in the outer wall 26. It will be appreciated that it is, thus, possible to ensure that by choosing the desired thickness for the inner and outer wall the electric field strength inside the inner wall can be kept smaller than the dielectric strength of the first material, and the electric field strength inside the outer wall can be kept smaller than the dielectric strength of the second material. Thus, the region of high electrical field strengths is removed from the first material with a lower dielectric strength to the second material with the higher dielectric strength.

[0050] The optimum thicknesses of the inner wall 24 and outer wall 26, e.g. for a given total wall thickness may be determined by the following method. An inner tubular wall with inner radius r1 and dielectric constant ε_{iw} and outer radius r2 covered with a outside wall with inner radius r2, dielectric constant ε_{ow} and outer radius r3 results in radial electrical field variation as a function of the radius r according to the following equations.

$$E_{iw}=V_{13}/(\varepsilon_{iw}\ r\ K),$$

and

$$E_{ow}=V_{13}/(\varepsilon_{ow}\ r\ K),$$

wherein V_{13} is the electrical potential difference across the (total of the inner and outer) tubular wall, E_{iw} is the maximum electric field in the inner layer, E_{ow} is the maximum electric field in the outer layer and $K=1/\varepsilon_{iw}\ln(r2/r1)+1/\varepsilon_{ow}\ln(r3/r2)$.

[0051] Fig. 2 shows a graph in which the highest electric field value occurring in a tubular wall comprising the inner wall and the outer wall is demonstrated.

[0052] In this example the inner wall 24 is alumina and the outer wall 26 is polyethylene, having dielectric constants of approximately 8 and 2, respectively. The dielectric strength values of optically transparent alumina and polyethylene are approximately 50 kV/mm and 160 kV/mm, respectively.

[0053] It is noted here that if a tubular wall is taken of only alumina (no outer wall of polyethylene) it is not possible to obtain the tubular wall with the small inner diameter of e.g. 0.5 mm and the small outer diameter of e.g. 2 mm, as this will result in the dielectric strength of alumina being exceeded if 50 kV is applied across the wall. This impedes miniaturisation of the source 1.

[0054] Fig. 2 shows a graph in which the highest electric field value occurring in a tubular wall with an inner radius of 0.25 mm and an outer radius of 1 mm, i.e. a wall thickness of 0.75 mm, when 50 kV is applied across the wall. In Fig. 2 the highest electrical field value is shown in the inner tubular wall 24 of alumina with an inner radius of 0.25 and an outer radius of r2 (lower curve in Fig. 2). Fig. 2 further shows the highest electrical field value in the outer tubular wall 26 of polyethylene with an inner radius of r2 and an outer radius of 1 mm (upper curve in Fig. 2). Both the highest electrical field values in the inner and outer wall are shown as a function of r2. Hence, the outer radius r2 of the inner wall ranges from 0.25 mm (only polyethylene) to 1 mm (only alumina) and the inner radius of the outer wall ranges from 0.25 mm (only polyethylene) to 1 mm (only alumina).

[0055] It can be seen from Fig. 2 that if, in this example, the outer radius of the inner wall of alumina approaches 1 mm, i.e. a wall thickness of the alumina inner wall of approximately 0.75 mm, the highest electric field in the inner wall exceeds the dielectric strength of alumina, so that electrical breakthrough in the inner wall might occur. It can be seen from Fig. 2 that if, in this example, the inner radius of the outer wall of polyethylene is less than approximately 0.3 mm or exceeds approximately 0.7 mm (crosshatched in Fig. 2), i.e. a wall thickness of the outer wall of polyethylene of more than approximately 0.65 mm or less than approximately 0.3 mm, the highest electric field in the outer wall exceeds the dielectric strength of polyethylene, so that electrical breakthrough in the outer wall might occur.

[0056] Thus, Fig. 2 suggests that for the tubular wall with the inner wall of alumina and the outer wall of polyethylene, wherein the total wall has an inner radius of 0.25 mm and an outer radius of 1 mm, the thickness of the outer wall is preferably between approximately 0.3 and 0.7 mm, more preferably approximately 0.5 mm (near the minimum of the upper curve of Fig. 2). Accordingly, the thickness of the inner wall is preferably between approximately 0.05 and 0.45 mm, more preferably approximately 0.25 mm.

[0057] It will be clear from Fig. 2 that applying a thin coating of polyethylene (e.g. < 100 μm), in this example would have the result that the dielectric strength of polyethylene would be exceeded by the highest electric field in the polyethylene, by far so that a high risk of electrical breakthrough in the polyethylene coating would arise.

[0058] Hence, it is possible to provide a wall 24,26 of the vacuum tube comprising the inner 24 and the outer wall 26, such that the total wall thickness is minimized, while breakthrough across the wall is substantially prevented. Thus, further miniaturisation of the miniature X-ray source may be achieved.

[0059] Fig. 1b shows a schematic sectional view of a variation of the embodiment according to Fig. 1a.

[0060] In Fig. 1b the source 1 is further provided with a tubular electrical conductor 27. In this example the tubular conductor 27 is placed between the inner and outer wall 24,26. It will be appreciated that the tubular conductor 27 may also be arranged on the inside of the inner wall 24 or on the outside of the outer wall. In Fig. 1b the tubular conductor 27 is electrically connected to the cathode 4. It will be appreciated that the tubular conductor 27 may also be maintained at an electric potential different from that of the cathode 4.

[0061] The tubular conductor 27 shapes the electric field around the cathode 4 such that the tubular conductor 27 acts as an electric lens. In this example the electric lens is dimensioned such that substantially all electrons emitted by the cathode 4 are aimed through the aperture 14 in the direction of the anode 2. Thus, substantially all electrons emitted by the cathode 4 are prevented from impacting the wall of the vacuum tube 8 in the region between the diaphragm 12 and the cathode 4, i.e. in the region of the vacuum tube 8 where, in use, the electric field is present. Hence, these electrons will not form electron sources at the inner side of the inner wall 24, so that the risk of electrical breakthrough is reduced. Further the risk of electrically charging the inner wall 24 is reduced.

[0062] Thus, the electric lens forms electron focussing means for directing, in use, the electrons emitted by the cathode 4 in a direction towards the anode 2, such that substantially all electrons emitted by the cathode 4 are prevented from impacting the wall of the vacuum tube 8, in this example in the region of the vacuum tube where, in use, the electric field is present.

[0063] It will be appreciated that the electric lens thus forms guiding means for guiding electrons and/or ions to prevent the electrons and/or ions from impacting a wall of the vacuum tube 8, e.g. in a region of the vacuum tube where, in use, an electric field is present.

[0064] It will be appreciated that the electric lens may be used to reduce the risk of electrical breakthrough independently of the directional barrier.

[0065] Fig. 3 shows a schematic sectional view of a second embodiment of a miniature X-ray source 1 according to the invention. In Fig. 3 the source 1 also comprises the anode 2, the cathode 4. and the vacuum tube 8 enclosing the inner space 10 in which a vacuum is present. In Fig. 3 the anode 2,2' and the diaphragm 12 also form the electrically conducting box 2,2',12 with the aperture 14 as entrance for the accelerated electrons.

[0066] In the example of Fig. 3 the cathode 4 is provided with a bore 40 which is in communication with a longitudinal bore 42 through which the inner space 10 can be evacuated. After evacuation a seal 44 may be sealed, e.g. by melting, welding, etc.

[0067] In the example of Fig. 3 the inner space 10 also comprises a getter material 46 for absorbing any free particles in the inner space for reducing the vacuum pressure inside the inner space 10. In this example, the getter material 46 is positioned at the cathode 4.

[0068] In the example of Fig. 3 the anode 2 comprises a window 28 coated with a high molecular mass electrical conductive coating, such as e.g. a 1-20 μm thick layer of tungsten, for generating X-ray radiation when impacted by electrons. The window 28 may be substantially, or at least partially, transparent to X-rays, e.g. alumina.

[0069] In the example of Fig. 3 the source 1 further comprises an exit window 31 which is substantially, or at least partially, transparent to X-ray radiation. In this example the X-ray radiation exits the source 1 mainly through the exit window. Thus substantially a directional source of X-ray radiation is obtained. This may e.g. be particularly useful in imaging or detection.

[0070] In the example of Fig. 3 the cathode 4 is of the cold cathode type. In this example the cathode 4 comprises a section 32 comprising carbon nanotubes for emitting electrons. The carbon nanotubes may be aligned mono-wall nanotubes, aligned multi-wall nanotubes, randomised mono-wall nanotubes or randomised multi-wall nanotubes.

[0071] It will be appreciated that the section 32 substantially acts as a randomly oriented source of electrons, emitting electrons both towards the anode 2 and towards the tubular housing 18.

[0072] In Fig. 3 the cathode 4 is concave, in a direction towards the anode 2. The cathode 4, thus, has a ring-shaped projection 34 which shapes the electric field around the cathode 4, more in particular around the electron source section 32, such that the projection 34 acts as the electric lens. In this example the electric lens is dimensioned such that substantially all electrons emitted by the cathode 4 are aimed through the aperture 14 in the direction of the anode 2. Thus, substantially all electrons emitted by the cathode 4 are prevented from impacting the wall of the vacuum tube 8 in the region between the diaphragm 12 and the cathode 4, i.e. in the region of the vacuum tube 8 where, in use, the electric field is present. Hence, these electrons will not form electron sources at the wall, so that the risk of electrical breakthrough is reduced. Further the risk of electrically charging the inner wall 24 is reduced.

[0073] When placed in a electrical field, local materials defects and roughness of materials initiate local high electrical field strengths. These locations act as electron source and often function as the origin of electrical breakthrough. In particular, triple junctions of metal, insulator and vacuum act as such and thus poses a risk for electrical breakthrough. In Fig. 3 tubular triple junctions are indicated with reference T.

[0074] In Fig. 3 the miniature X-ray source 1 comprises a first electrically conducting, e.g. metal, shield 36 around the tubular housing 18 adjacent the anode 2. Further, the miniature X-ray source 1 comprises a second electrically conducting, e.g. metal, shield 38 around the tubular housing 18 adjacent the cathode 2. The end of the first shield 36 towards the cathode 4 extends around the outside of the tubular housing 18 as far as the end of the anode 2. Thus, there is substantially no electrical field near the triple junction T adjacent the anode. Thus, the risk of electrical breakthrough is reduced. Similarly, the end of the second shield 38 towards the anode 2 extends around the outside of the tubular housing 18 as far as the end of the cathode 4. Thus, there is substantially no electrical field near the triple junction T adjacent the cathode. Thus, the risk of electrical breakthrough is reduced.

[0075] In the example of Fig. 3 the second shield 38 may also be dimensioned such that the second shield 38 acts as an electric lens. In this example this electric lens is dimensioned such that aids in aiming substantially all electrons emitted by the cathode 4 through the aperture 14 in the direction of the anode 2.

[0076] Fig. 4 shows a schematic sectional view of a second embodiment of a miniature X-ray source 1 according to the invention. In Fig. 4 the source 1 also comprises the anode 2, the cathode 4 and the vacuum tube 8 enclosing the inner space 10 in which a vacuum is present. In Fig. 4 the anode 2,2' and the diaphragm 12 also form the electrically conducting box 2,2',12 with the aperture 14 as entrance for the accelerated electrons. In Fig. 4 the anode 2 comprises the window 28 coated with the high atomic mass electrical conductive coating, such as e.g a 1-10 μm thick layer of tungsten.

[0077] In Fig. 4 the miniature X-ray source 1 also comprises the first electrically conducting shield 36 around the tubular housing 18 adjacent the anode 2 and the second electrically conducting shield 38 around the tubular housing 18 adjacent the cathode 2. In the example of Fig. 4 the first and second shield 36, 38 are formed by a metallic coating on the outer side of the vacuum tube 8. The first shield 36 is electrically connected to the anode 2, e.g. via the tubular portion 2'. The second shield 38 is electrically connected to the cathode 4.

[0078] In the example of Fig. 4 a high-resistivity coating 48 is applied on the outer side of the vacuum tube 8, in electrical connection with the first and second shield 36,38 respectively. An electrical resistivity of the high-resistivity coating is preferably in the rang 10^6 -10^{10} ohm/cm. It will be appreciated that the high-resistivity coating 48 may also be applied on the inner side of the vacuum tube 8, in electrical connection with the anode and the cathode. Thus, the high-resistivity coating may enforce a gradual linear voltage distribution along the isolating tubular housing 18 as a result of a small electric current (e.g. 0.1 to 100 μA) that may flow through the high-resistivity coating.

[0079] In the example of Fig. 4 the anode 2 is maintained at earth electric potential and the cathode 4 is maintained at a negative high voltage, e.g. -60 kV. Thus, easy cabling of the source 1 is possible.

[0080] Fig. 5 shows a schematic sectional view of an array of miniature X-ray sources 1 according to a fourth embodiment of invention. Such array may e.g. be desirable when a small X-ray source is required with a large surface area of substantially homogeneous X-ray radiation. In Fig. 5 the sources 1 also comprises the anode 2, the cathode 4 and the vacuum tube 8 enclosing the inner space 10 in which a vacuum is present. In Fig. 4 the anode 2,2' and the diaphragm 12 also form the electrically conducting box 2,2',12 with the aperture 14 as entrance for the accelerated electrons. In Fig. 4 the anode 2 comprises the window 28 coated with the high molecular mass electrical conductive coating, such as e.g. a 1-10 μm thick layer of tungsten. In the example of Fig. 5 the ring-shaped projection 34 which shapes the electric field around the cathode 4, more in particular around the electron source section 32, such that the projection 34 acts as an electric lens is not integral with the cathode 4, but designed as a separate part. The ring-shaped part 34 may be maintained at an electronic potential that differs from the electric potential of the cathode 4. The ring-shaped part 34 may e.g. be electrically conducting connected to a voltage supply line 35.

[0081] In Fig. 5 the beam of electrons emitted by the cathode 4, transmitted through the aperture 14 and impacted on the anode 2 is indicated with broken lines.

[0082] The invention is by no means limited to the above exemplary embodiments.

[0083] It is for instance possible to provide a miniature X-ray source according to the invention for providing X-ray radiation which is emitted intermittently, e.g. by sequentially switching a supply power to the cathode and/or the anode on and off.

[0084] In the examples an electric lens is used for preventing electrons emitted by the cathode from impacting the wall of the vacuum tube in the region where, in use, the electric field is present. It will be appreciated that alternatively, or additionally, a magnetic lens may be used.

[0085] In the examples the cold cathode comprises carbon nanotubes as electron source. Alternative "hot" or "cold" electron sources can also be used, such as metal-insulator-metal stacks (MIM), piezo-electric crystals or thermionic surfaces (e.g a tungsten filament).

[0086] In the examples of figures 3, 4,and 5, the exit window is flat. It will be appreciated that the exit window can also have other shapes such as conical or dome-shaped.

[0087] In the examples the diaphragm and the anode form a substantially cylindrical box. It will be appreciated that also other shapes are possible. The box may e.g. be conical, frustoconical, dome-shaped, block-shaped, pyramidal, etc.

[0088] It is also possible that within the vacuum tube an, e.g. grid shaped, electron absorbing element is disposed between the cathode and the directional barrier for absorbing any electrons being reflected from the barrier towards the cathode. The grid-shaped absorbing element may e.g. be maintained at an electrical potential which is slightly higher than that of the anode.

[0089] All such variations are considered to fall within the scope of the invention.

Claims

1. Miniature X-ray source comprising:

   a vacuum tube containing a cathode and an anode spaced apart from each other; and
   guiding means for guiding electrons and/or ions to prevent the electrons and/or ions from impacting at least a part of a wall of the vacuum tube.

2. Miniature X-ray source according to claim 1, wherein the guiding means are arranged for guiding the electrons and/or ions to prevent the electrons and/or ions from impacting at the wall of the vacuum tube in a region of the vacuum tube where, in use, an electric field is present.

3. Miniature X-ray source according to claim 1 or 2, wherein the guiding means comprise
   a directional barrier interposed between the cathode and the anode wherein the barrier is arranged to transmit, in use, electrons emitted by the cathode towards the anode, and wherein the barrier is arranged to, in use, substantially prevent electrons and/or ions to pass the barrier in the direction of the anode towards the cathode.

4. Miniature X-ray source according to claim 3, wherein the directional barrier is an electrically conducting diaphragm comprising an aperture, wherein the diaphragm is arranged to be maintained at the same electric potential as the anode.

5. Miniature X-ray source according to claim 4, wherein the anode and the diaphragm together form the electrically conducting walls of a chamber which is preferably closed except for the aperture.

6. Miniature X-ray source according to any one of claims 1-5, wherein the guiding means comprise
   electron focussing means for directing, in use, the electrons emitted by the cathode in a direction towards the anode, such that substantially all electrons emitted by the cathode are prevented from impacting at least the part of the wall of the vacuum tube.

7. Miniature X-ray source according to claim 3 and 6, wherein the electron focussing means are arranged for directing, in use, the electrons emitted by the cath-

ode in a direction such that substantially all electrons emitted by the cathode are transmitted by the directional barrier.

8. Miniature X-ray source according to claim 4 and 7, wherein the electron focussing means are arranged for directing substantially all electrons emitted by the cathode through the aperture in the direction of the anode.

9. Miniature X-ray source according to any one of claims 6-8, wherein the electron focussing means comprise an electric and/or magnetic lens.

10. Miniature X-ray source according to claim 9, wherein the cathode is concave, in a direction towards the anode, wherein the concave shape acts as the electric lens for directing, in use, the electrons emitted by the cathode in a direction such that substantially all electrons emitted by the cathode are transmitted by the directional barrier.

11. Miniature X-ray source according to any one of the preceding claims, wherein within the vacuum tube a grid shaped electron absorbing element is disposed between the cathode and the directional barrier for absorbing any electrons being reflected from the barrier towards the cathode.

12. Miniature X-ray source according to any one of the preceding claims, wherein the cathode is of a cold cathode type comprising carbon nanotubes for emitting electrons.

13. Miniature X-ray source according to claim 12, wherein the carbon nanotubes are aligned mono-wall nanotubes, aligned multi-wall nanotubes, randomised mono-wall nanotubes or randomised multi-wall nanotubes.

14. Miniature X-ray source according to any one of the preceding claims, wherein the vacuum tube is at least partly made of an electrically isolating material.

15. Miniature X-ray source according to claim 14, wherein the vacuum tube comprises an inner wall, of a first material and an outer wall of a second material.

16. Miniature X-ray source according to claim 15, wherein a dielectric constant of the first material is higher than a dielectric constant of the second material, and wherein a dielectric strength of the second material is higher than a dielectric strength of the first material.

17. Miniature X-ray source according to claim 16, wherein the first material is a ceramic material, such as aluminium oxide, and the second material is a polymer material, such as polyethylene.

18. Miniature X-ray source according to claim 16 or 17, wherein the thickness of the inner wall and the outer wall is such that, in use, the electric field strength inside the inner wall is smaller than the electric field strength in the outer wall.

19. Miniature x-ray source according to any one of the preceding claims, wherein the vacuum tube comprises a substantially tubular housing of an electrically isolating material having an electrically conducting first cap or first plug associated with the anode at a first end of the tubular housing and an electrically conducting second cap or second plug associated with the cathode at the other, second end of the tubular housing.

20. Miniature X-ray source according to any one of the preceding claims, wherein the vacuum tube at a triple junctions of an electrical conductor, electrical insulator and vacuum is provided with an electrically conducting layer at the outside surface of the electrically isolating tubular housing.

21. Miniature X-ray source according to any one of the preceding claims, wherein the inner side and/or outer side of the vacuum tube is provided with a high electrical resistivity coating, which is electrically conducting connected to the anode and the cathode.

22. Miniature X-ray source according to any one of the preceding claims, wherein the anode is provided with a flat X-ray emitting surface.

23. Miniature X-ray source according to anyone of the preceding claims, wherein the anode comprises a first layer and a second layer, wherein the first layer is made of a first material, which first material is at least partly transparent to X-ray radiation, such as alumina, and wherein the second layer comprises a second material, e.g. tungsten, which second material generates X-ray radiation in response to electrons impacting on the second material.

24. Miniature X-ray source according to claim 12, wherein the cathode is deposited on the getter material.

25. Miniature X-ray source according to any one of the preceding claims, further comprising an exit window which is at least partially transparent for X-ray radiation, wherein the anode is displaceably accommodated within said X-ray source with respect to the exit window.

26. Miniature X-ray source according to any one of the preceding claims, wherein the X-ray source has a cylindrical shape with a diameter of 1-2.5 mm and a length of 2-3 cm.

27. Miniature X-ray source according to any one of the preceding claims, wherein the source device comprises cooling means for cooling at least said anode.

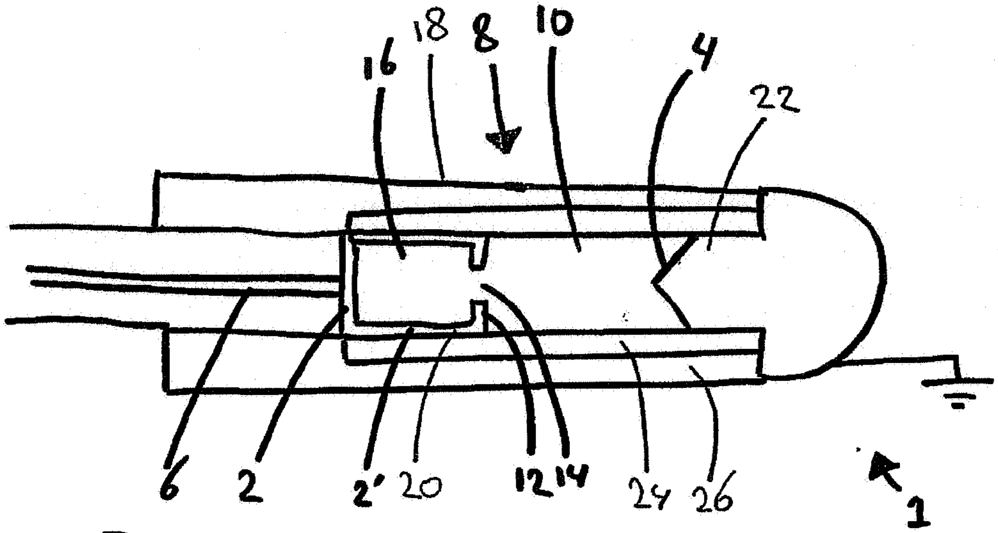
16
18
8
10
4
22
6
2
2'
20
12
14
24
26
1

Fig. 1a

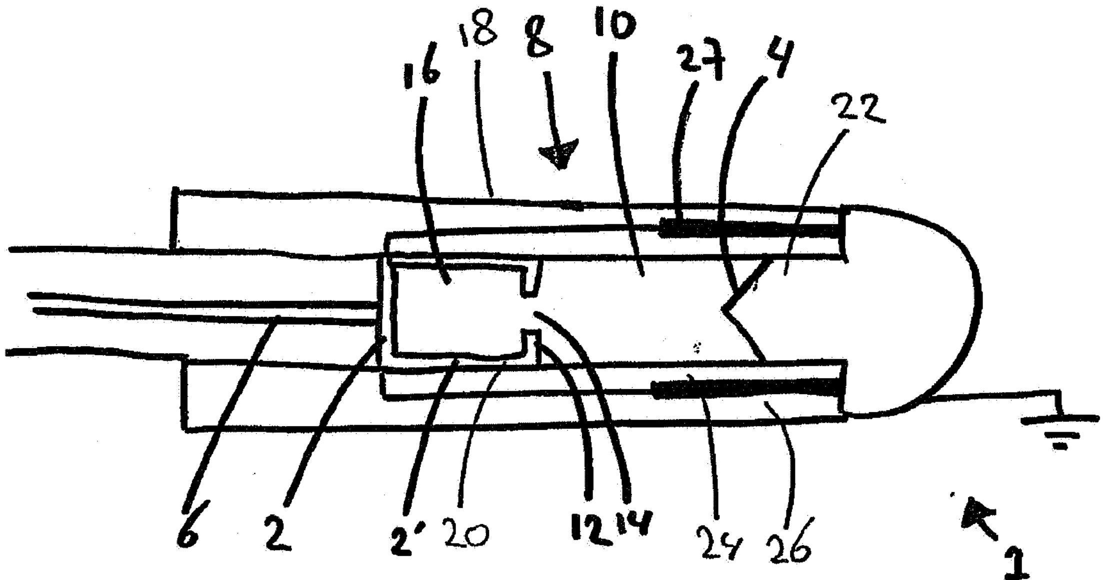
16
18
8
10
27
4
22
6
2
2'
20
12
14
24
26
1

Fig. 1b

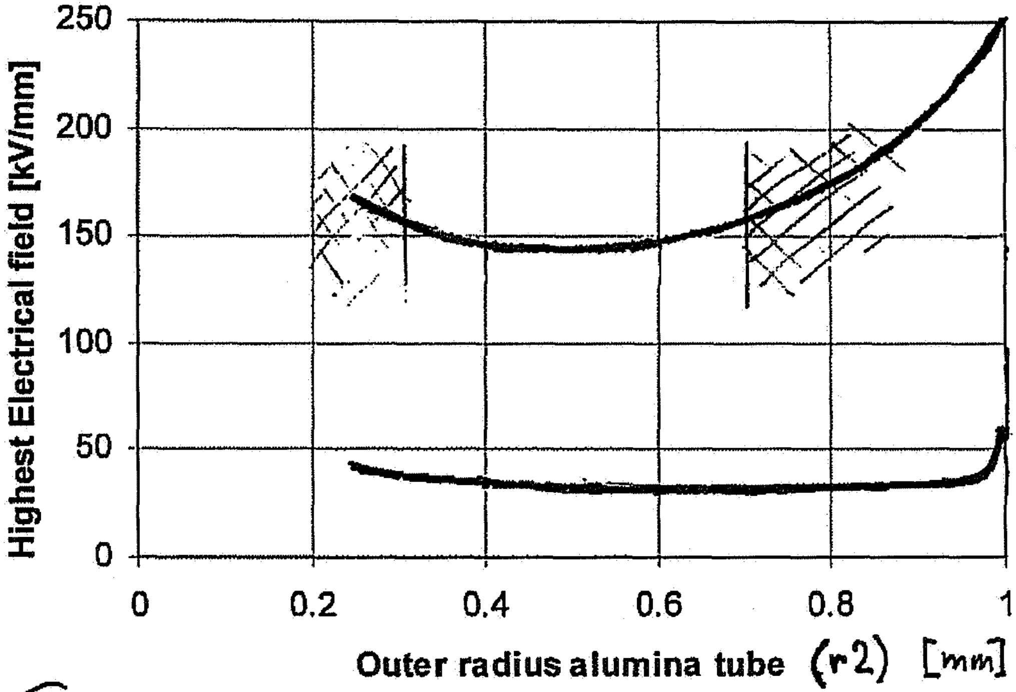
250
200
150
100
50
0
Highest Electrical field [kV/mm]
0
0.2
0.4
0.6
0.8
1
Outer radius alumina tube (r2) [mm]

Fig. 2

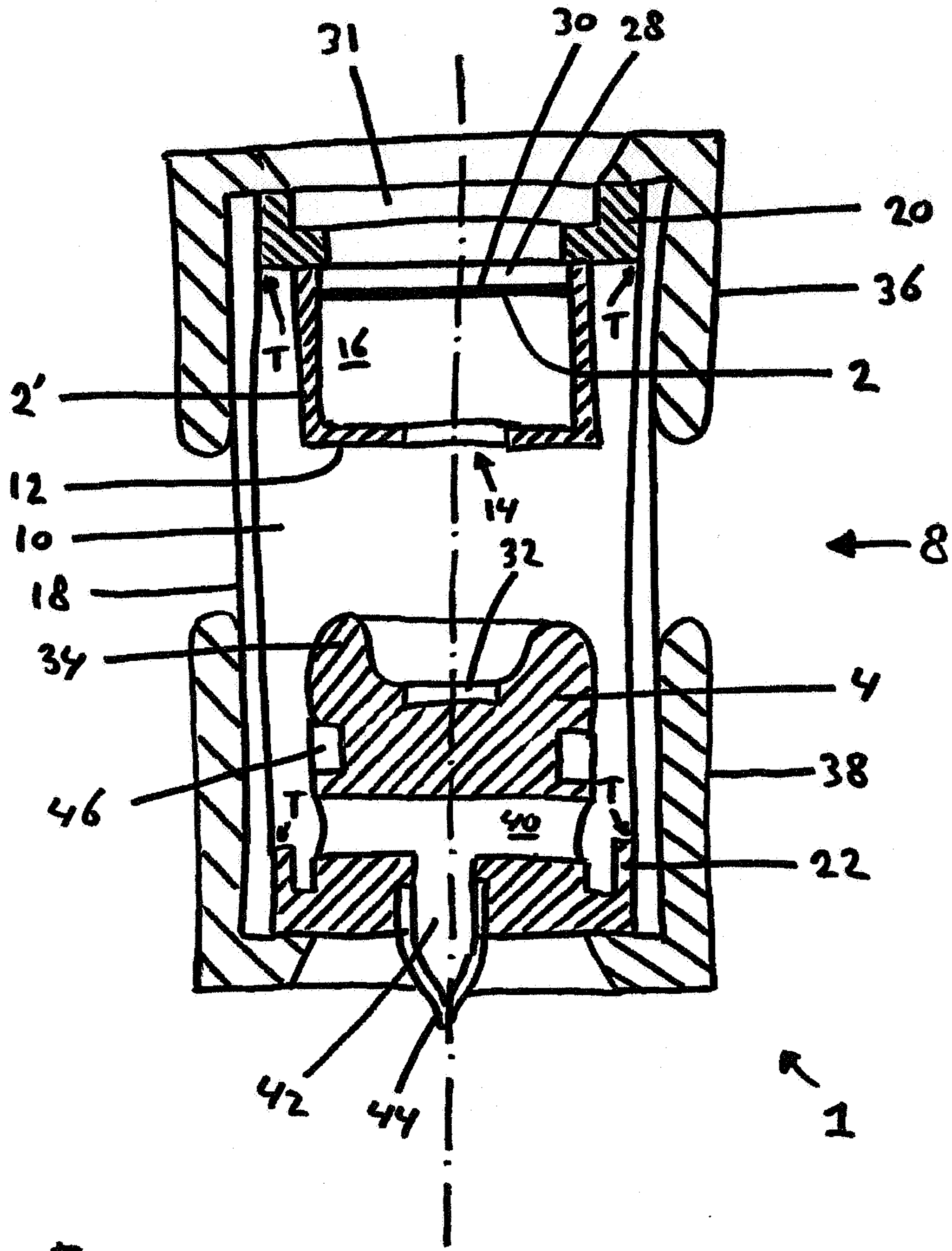

Fig. 3

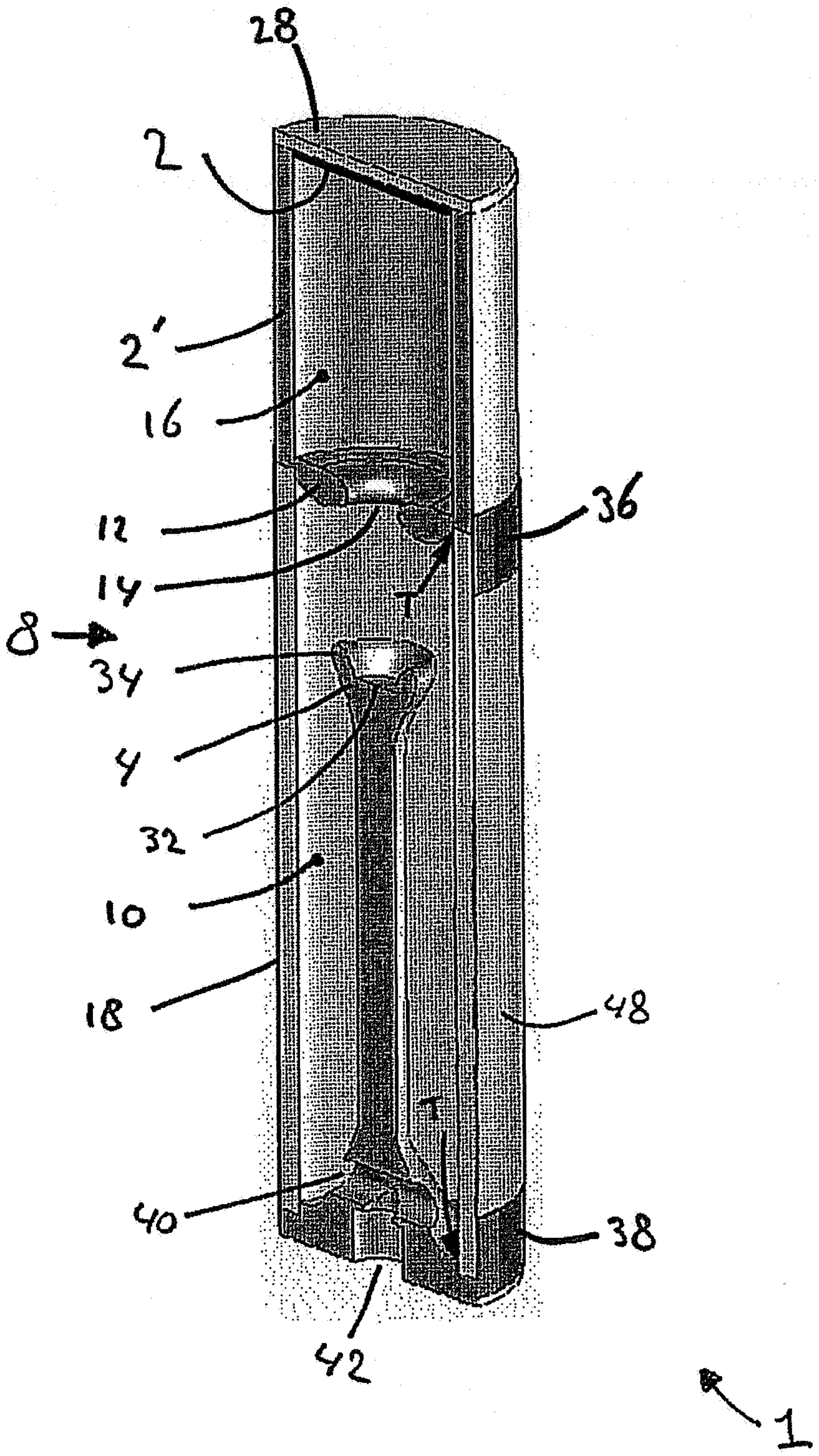

Fig. 4

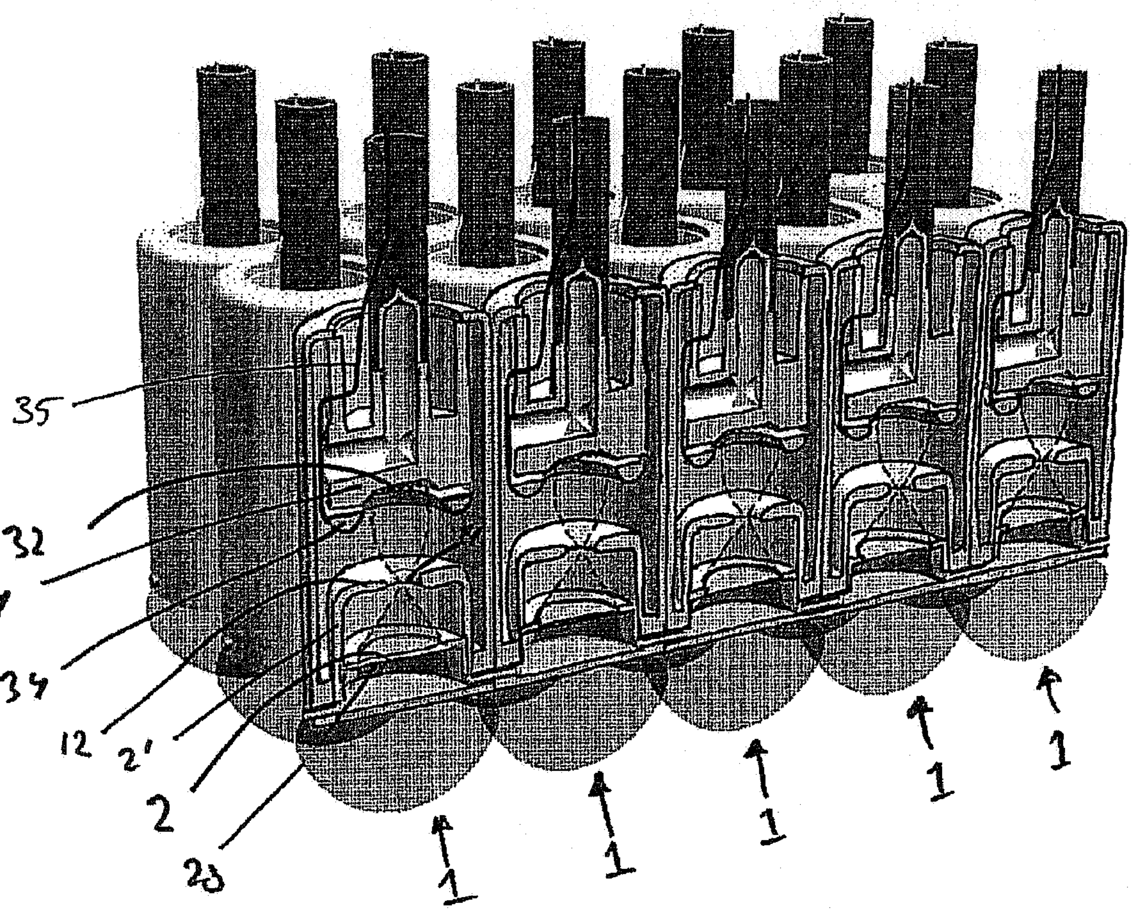

Fig. 5

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EUROPEAN SEARCH REPORT

Application Number
EP 07 11 0601

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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~~The present search report has been drawn up for all claims~~

Place of search	Date of completion of the search	Examiner
Munich	19 May 2008	Angloher, Godehard

CATEGORY OF CITED DOCUMENTS

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EUROPEAN SEARCH REPORT

Application Number
EP 07 11 0601

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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			TECHNICAL FIELDS SEARCHED (IPC)

~~The present search report has been drawn up for all claims~~

Place of search	Date of completion of the search	Examiner
Munich	19 May 2008	Angloher, Godehard

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L : document cited for other reasons

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EPO FORM 1503 03.82 (P04C01)

European Patent
Office

Application Number
EP 07 11 0601

CLAIMS INCURRING FEES

The present European patent application comprised at the time of filing claims for which payment was due.

- [ ] Only part of the claims have been paid within the prescribed time limit. The present European search report has been drawn up for those claims for which no payment was due and for those claims for which claims fees have been paid, namely claim(s):

- [ ] No claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for those claims for which no payment was due.

LACK OF UNITY OF INVENTION

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

see sheet B

- [ ] All further search fees have been paid within the fixed time limit. The present European search report has been drawn up for all claims.

- [ ] As all searchable claims could be searched without effort justifying an additional fee, the Search Division did not invite payment of any additional fee.

- [X] Only part of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the inventions in respect of which search fees have been paid, namely claims:

  1-11,14-19

- [ ] None of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims, namely claims:

- [ ] The present supplementary European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims (Rule 164 (1) EPC).

European Patent Office

LACK OF UNITY OF INVENTION SHEET B

Application Number
EP 07 11 0601

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

1. claims: 1-11

   features of claim 1;
   electrons / ions are prevented from impacting the wall in a region where an electric field is present (in use)
   ---

2. claims: 1,12,13,24

   features of claim 1;
   cold cathode comprising carbon nanotubes
   ---

3. claims: 1,14-19

   features of claim 1;
   vacuum tube at least partially made of electrically isolating material
   ---

4. claims: 1,20

   features of claim 1;
   outside surface of triple junctions provided with conducting layer
   ---

5. claims: 1,21

   features of claim 1;
   inside and / or outside of vacuum tube provided with high resistivity coating connected to anode and cathode
   ---

6. claims: 1,22

   features of claim 1;
   anode has flat X-ray emitting surface
   ---

7. claims: 1,23

   features of claim 1;
   dual layer anode
   ---

8. claims: 1,25

   features of claim 1;
   anode displaceably located with respect to exit window

European Patent Office

LACK OF UNITY OF INVENTION SHEET B

Application Number
EP 07 11 0601

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

9. claims: 1,26

features of claim 1;
cylindrical X-ray source with diameter of 1 - 2.5 mm and length of 2 - 3 cm

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10. claims: 1,27

features of claim 1;
cooling means at least for anode

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 07 11 0601

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
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19-05-2008

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