

March 14, 1967

W. P. DYKE ETAL

3,309,523

X-RAY TUBE HAVING FIELD EMISSION CATHODE AND EVAPORATIVE
ANODE IN COMBINATION WITH ELECTRICAL PULSER MEANS

Filed June 24, 1963

2 Sheets-Sheet 1

FIG. 1

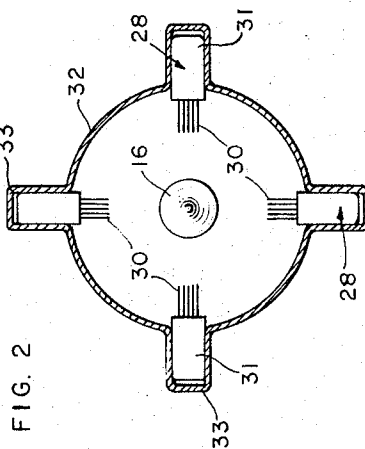
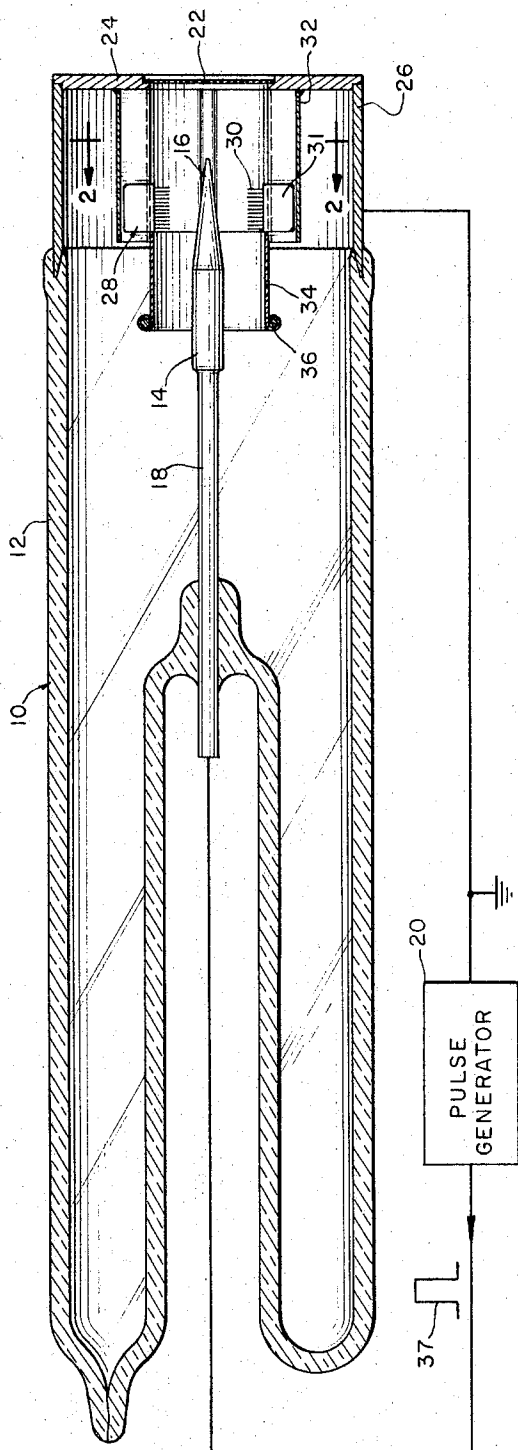


FIG. 2

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FIG. 4

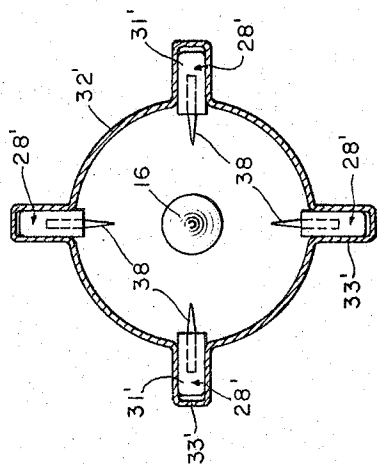


FIG. 6

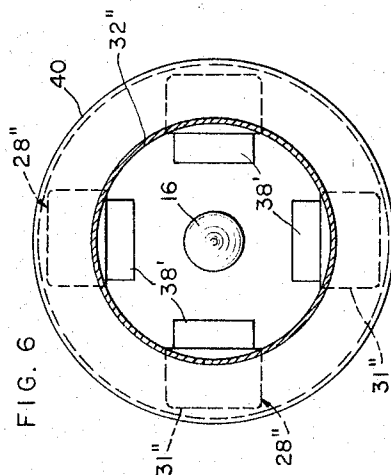


FIG. 3

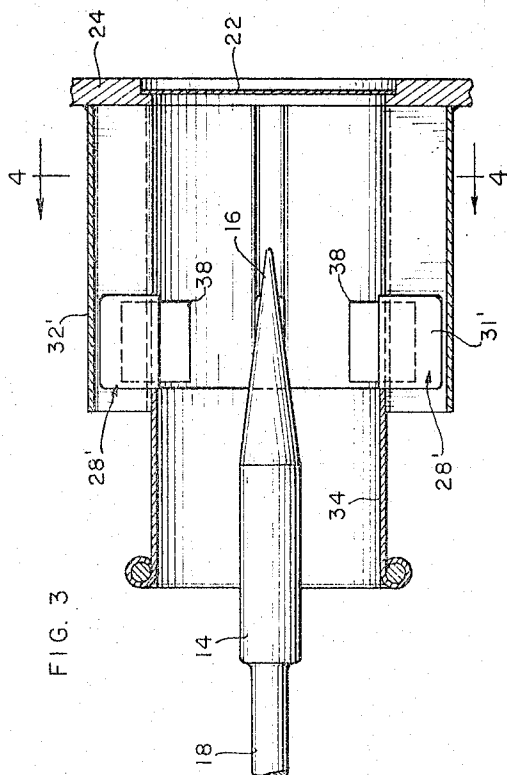
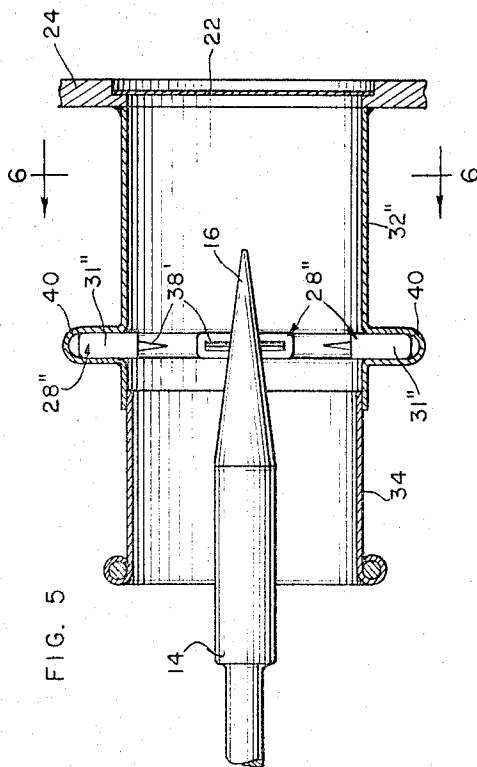


FIG. 5



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X-RAY TUBE HAVING FIELD EMISSION CATHODE AND EVAPORATIVE ANODE IN COMBINATION WITH ELECTRICAL PULSER MEANS

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8 Claims. (Cl. 250-102)

The subject matter of the present invention relates generally to X-ray tubes and in particular to an X-ray tube having a cathode which produces free electrons by field emission and an X-ray emitting anode of extremely small size which is cooled by the evaporation of metal from the surface of such anode. The type of electron emission employed in the operation of the X-ray tube of the present invention may be vacuum arc field emission which involves the generation of positive ions of cathode metal vapor simultaneously with the field emission of electrons from the cathode in order to neutralize the negative space charge surrounding such cathode. This increases the electron current flowing from the cathode to the anode by a very great amount so that such current may be of the order of 1000 to 2000 amperes for a short period of time to produce X-ray pulses of high intensity.

The X-ray tube of the present invention is especially useful as a small source of high intensity X-ray pulses of short duration which may be employed for ballistic purposes to stop the motion of high speed phenomena, for medical diagnosis requiring high resolution, and for industrial application requiring deep penetration. In order to produce these X-ray pulses, a plurality of short electrical pulses of high voltage and high current on the order of 75 to 600 kilovolts and 1400 to 2000 amperes are applied between the cathode and anode of such tube. These electrical pulses are substantially rectangular voltage pulses having extremely short rise times on the order of .005 microsecond and narrow pulse widths of approximately .07 microsecond and may be produced, for example, by the pulse generator shown in copending U.S. application Ser. No. 103,796, filed Apr. 18, 1961, by W. P. Dyke et al. entitled, High Voltage Pulser, now U.S. Patent No. 3,248,574.

The X-ray tube of the present invention has several advantages over conventional small source X-ray tubes, including those employing rotating anodes or hollow anodes having passageways for the circulation of liquids therethrough in order to cool such anodes, since the evaporative anode employed in such tube has a much simpler structure than anodes of previous tubes because it utilizes the evaporation of metal from the surface of the anode to cool such anode. In addition, the small size of the evaporative anode of the present invention enables the electron focal spot produced thereon which is the source of X-rays, to be as small as 1 millimeter in diameter. As a result, the X-ray photographs produced by such small source have better resolution than those produced by conventional tubes having larger focal spots. In addition, the present X-ray tube has a simpler field emission cathode structure, and is greatly reduced in size with respect to conventional tubes operating at comparable voltage. As a result of their simple structure, the tubes of the present invention are less expensive to manufacture. Another

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advantage of the present tube is that it is of a relatively low impedance during conduction which can be made on the order of 70 ohms to match the characteristic impedance of a coaxial cable or other transmission line so that the pulser referred to above can be connected to such tube through a transmission line without distorting the wave form of the voltage pulses transmitted therefrom.

An additional advantage of the tube of the present invention is that the metal vapor produced by the evaporative anode acts as a getter material after it has been deposited as a coating upon a portion of the wall of the tube envelope. This getter coating retains the original high vacuum within the tube and even improves such vacuum by absorbing residual gases within such tube. In order to prevent the metal coating from acting as a short circuit connection on the envelope wall between the anode and cathode of the X-ray tube, a shield member is provided around the anode of such tube to mask a portion of the envelope from such metal coating. This increases the useful life of the X-ray tube as much as 10 times the life of such tube without the shield.

The present X-ray tube is a diode, as compared with the triode tubes in U.S. Patents 2,311,705 and 2,720,607 of Slack and Criscuolo, so it is simpler and more reliable in operation, as discussed in our copending U.S. patent application Ser. No. 114,125 entitled, "Vacuum Arc X-Ray Tube, System and Method," and produces shorter length X-ray pulses than these previous triggered tubes. It has also been discovered that a plurality of X-ray pulses may be employed for a single exposure period in order to enable the penetration of greater thicknesses than would be possible with a single X-ray pulse. This multiple pulse exposure technique is even possible when employed for the diagnosis of human beings where there is some movement of the object, because the X-ray pulses are of extremely short time duration and of a high frequency.

It is therefore one object of the present invention to provide an improved X-ray tube of simple structure and small size which is inexpensive to manufacture.

Another object of the present invention is to provide an improved X-ray tube whose anode is cooled by the evaporation of metal therefrom.

A further object of the invention is to provide an improved X-ray tube in which a field emission cathode and an evaporative anode are employed in order to produce X-ray pulses of extremely high intensity by vacuum arc operation.

An additional object of the present invention is to provide an improved X-ray tube in which an anode of small size enables X-rays to be emitted from an extremely small focal spot to thereby produce high resolution X-ray images.

Still another object of the invention is to provide an improved method of operating an X-ray tube in which the anode of such tube is cooled by evaporating metal from such anode, and in which a plurality of X-ray pulses are employed to produce a single exposure of deeper penetration.

A still further object of the present invention is to provide an improved X-ray tube having a low conduction impedance which can be matched to the characteristic impedance of a transmission line connecting such tube to a source of high voltage pulses, and in which a coating of anode metal is produced on the envelope of the tube dur-

ing the operations of such tube which acts as a getter to maintain a high vacuum within such envelope and to prolong the useful life of such tube.

Other objects and advantages of the present invention will be apparent from the following detailed description of certain embodiments thereof and from the attached drawings of which:

FIG. 1 is a longitudinal sectional view of one embodiment of the X-ray tube of the present invention connected to a source of electrical pulses shown diagrammatically;

FIG. 2 is a vertical sectional view taken along the line 2—2 of FIG. 1;

FIG. 3 is an enlarged, partial sectional view of another embodiment of the cathode structure of the X-ray tube of the present invention;

FIG. 4 is a vertical sectional view taken along the line 4—4 of FIG. 3;

FIG. 5 is an enlarged partial sectional view similar to FIG. 3 of a third embodiment of the cathode structure; and

FIG. 6 is a vertical sectional view taken along line 6—6 of FIG. 5.

As shown in FIGS. 1 and 2, the X-ray tube 10 of the present invention includes an envelope 12 of glass or other insulating material having a reentrant portion which forms a vacuum-tight seal with an anode 14 of tungsten, molybdenum or other refractory metal which is a good source of X-rays. The enlarged end of the anode 14 terminates in a conical target portion 16 having a maximum diameter of from one to ten millimeters, the diameter of such target usually being in the smaller portion of the range. The other end of such anode is formed by a stem portion 18 which extends through the envelope 12 to the exterior thereof for electrical connection to a pulse generator 20 which may be similar to that shown in the copending U.S. patent application Ser. No. 103,796 referred to above. The envelope 12 may be provided with a thin window 22 of the nickel-iron-cobalt alloy sold under the trade name "Kovar," beryllium or other suitable relatively X-ray transparent material extending substantially perpendicular to the axis of the anode 14 adjacent the target portion 16 so that X-rays emitted by such target portion are transmitted through the window with substantially no absorption. The window 22 may, for example, be approximately .003 inch thick and .562 inch in diameter. Such window is secured over a circular aperture in a mounting disk 24 of nickel by brazing or the like. The circular mounting disk is also brazed to one end of a hollow, circular support cylinder 26 of Kovar or other suitable metal while the other end of such support cylinder is sealed to the glass envelope 12.

The cathode structure of the X-ray tube of the present invention may include from two to sixteen field emission cathodes 28 which are supported in annular spaced relationship about the conical target portion 16 of the anode. Each of the field emission cathodes 28 may contain several hundred spaced needle projections 30 which extend substantially parallel to each other from a common rectangular support block 31 toward the anode. Each of the needle projections 30 is provided with a sharp point having a small radius of curvature in the order of 10^{-3} to 10^{-5} centimeters so that the needles are capable of emitting electrons by field emission from their points when a high potential gradient exists at such points. This high electrical field gradient is produced when a fast rising voltage pulse is applied by pulse generator 20 between the anode 14 and the cathodes 28 which may be grounded by supporting them on the mounting disk 24. The increased electrical field gradient produced by the sharp needles causes field emission earlier on the leading edge of the voltage pulse than previous cathodes of more blunt configuration, which results in a faster rising current pulse between the cathode needles and the anode of the X-ray tube. This enables the production of shorter length X-ray pulses on the order of 30 to 70 nanoseconds which

make radiographs of high velocity ballistic events with better resolution, and also reduces the spike overshoot on the leading edge of the voltage pulse so that there is less of a problem of undesirable arcing to the tube housing (not shown). The cathodes 28 are described in detail in copending U.S. patent application Ser. No. 114,125 entitled, "Vacuum Arc X-Ray Tube System and Method," filed June 1, 1961, by W. P. Dyke et al., now U.S. Patent No. 3,174,043 which also discusses additional advantages of the present tube including longer tube life and more reliable operation resulting from the use of a plurality of cathode needles.

A cathode mounting cylinder 22 which may be made of nickel, stainless steel or other suitable metal is welded, brazed or otherwise fastened at one end thereof to the mounting disk 24 and is also secured to the support blocks 31 of the cathode 28. The needle blocks 31 may be welded within four longitudinal folds 33 in the mounting cylinder 32 so that they extend substantially parallel to the axis of anode 14 with their needle projections 30 pointing substantially perpendicular to such axis.

A tubular shield member 34 of nickel or other suitable metal is attached to the end of the mounting cylinder 32 adjacent cathodes 28 so that it extends, around the target portion 16 and along the anode 14 to a flared end remote from such target portion. The shield member 34 surrounds that portion of the target 16 which extends out of the cathode mounting cylinder 22 and is positioned in the path between the target portion and the glass to metal seal area of envelope 12 and the support cylinder 26. This enables the shield to function as a mask to prevent anode metal evaporated from the anode target, from condensing on the envelope 12 adjacent such seal area so that a short-circuit path is not developed between the anode stem 18 and the cathodes 28 through support cylinder 26, during the operation of such device. The flared end of the shield member 34 may be provided by rolling a portion of such shield member over a nickel wire 36 about .025 inch in diameter. This provides a rounded corner at the end of the shield and decreases the potential gradient existing at the end of the shield to prevent arcing between such shield and the anode.

During the operation of the X-ray tube of FIGS. 1 and 2, a high voltage, high current pulse 37 of fast rise time and short duration is applied from the pulse generator 20 between the anode and cathode of such tube. For the tube shown, this rectangular pulse may be in the order of 150 kilovolts, 2000 amperes and may have a width of .07 microsecond. The application of this pulse 39 causes the field emission of electrons from one or more of the needle projections 30 on each of the cathodes 28, and also causes some of the metal of such needle projections to evaporate so that positive ions of cathode metal are produced in the vicinity of the cathodes. These positive ions neutralize the negative space charge ordinarily produced surrounding such cathodes and enables an extremely large electron current to flow from the needle projections 30 to the target portion 16 of the anode. As the electrons approach the target portion of the anode, they repel each other and produce a substantially uniform cloud of electrons which completely surrounds such target portion before bombarding it from substantially all directions to produce a small annular focal spot thereon which is less than 10 millimeters in diameter. The X-rays emitted from the focal spot produced on the target portion 16 of the anode are projected through the window 22 at the end of the X-ray tube as mentioned previously.

The use of a small diameter anode 14 creates a cooling problem which could not be solved by conventional cooling techniques employed in tubes having rotating anodes or hollow, liquid cooled stationary anodes. However, it has been found that the controlled evaporation of metal from the surface of the anode during the operation of the tube can be employed to cool such anode without effecting the performance of the tube, if the shape of the

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anode is such that the evaporation does not change its configuration materially. This evaporative anode cooling can be accomplished only if the energy of the electrons striking such anode exceeds a predetermined minimum level which, in the case of a tungsten anode is about 20 joules/cm.². This evaporative cooling has been performed at electron energy distribution up to 40 joules/cm.² and does not seem to be affected by changes in the diameter of the anode within certain limits because the voltage pulse is terminated before there is any appreciable heat conduction within the anode. However, changes in anode material obviously do affect the minimum energy level required for evaporative cooling so that this will vary with different refractory metals. The evaporated metal from the anode condenses on the glass envelope 12 so that such condensed metal could soon short-circuit the anode stem 18 to the support cylinder 26. However, the presence of the shield member 34 prevents this from happening because such shield member masks that portion of the envelope adjacent the support cylinder 26 and prevents evaporated anode metal from condensing thereon as mentioned previously. Thus, the shield member 34 increases the life of the X-ray tube a very considerable amount by as much as a factor of 10. It should be noted that the anode metal which condenses on the envelope 12 also performs a useful function since it serves as a getter to absorb gases remaining within the envelope and to maintain the tube under a high vacuum. Also the voltage pulses 37 applied between the cathode and anode are of extremely short duration so that the positive ions of metal evaporated from such anode do not reach the cathodes 28 and do not contaminate the electron emitting surface of the cathodes since the pulse is terminated before the metal ions can reach such cathodes. Of course, it is also possible to make the anode target 16 and cathode needle projections 30 out of the same material so that contamination is not a problem as it is when dissimilar metals are employed.

FIGS. 3 and 4 show another embodiment of the cathode structure of the tube 10 including cathodes 28' which each employ a knife-edge member 38 in place of the needle projections 30. This knife-edge member 38 may be similar in form to a razor blade and may have an electron emitting edge with a radius of curvature from 10⁻³ to 10⁻⁵ cm. The rear end of the blade is embedded in a support block 31' forming part of the cathode structure 28'. The support blocks 31' may be welded within the folds 33' of the mounting sleeve 32' in a similar manner to the cathodes 28 of FIGS. 1 and 2. Thus, the knife-edge members 38 may extend longitudinally along the axis of the anode 14 substantially parallel to such axis. While four cathodes 28' are shown, any suitable number of such cathodes may be equally spaced about the target portion 16 of the anode or one such cathode may be employed.

A third embodiment of the cathode structure in the X-ray tube 10 is shown in FIGS. 5 and 6. It includes cathodes 28'' secured to a modified mounting sleeve 32'' which is provided with an annular fold 40. In this embodiment the cathodes 28'' are similar to the cathodes 28' of FIGS. 3 and 4, but are positioned with the knife-edge members 38' extending substantially perpendicular to the axis of the anode 14 so that they form arcs on a circle which is concentric with the axis of such anode. However, it would also be possible to form these knife-edge members 38' as a single, annular ring whose inner edge serves as the electron emitting surface. In the embodiment of the cathode structure shown in FIGS. 5 and 6, the annular focal spot produced on the target portion 16 of the anode by the electrons emitted by the knife-edge members 38' will be of a smaller width than the focal spot produced by the cathode structures of FIGS. 3 and 4. It should be noted that the needle cathodes 28 of FIGS. 1 and 2 may also be supported substantially

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perpendicular to the axis of the anode 14, similar to the knife-edge cathodes of FIGS. 5 and 6.

While the target portion of the anode may be made in any convenient shape which does not deform during the evaporation of metal from such target portion, it appears that the conical shape of FIGS. 1 and 2 may be most desirable. Also the diameter of the anode may vary over a range of approximately one to ten millimeters and without preventing the evaporative cooling operation of such anode which is controlled by many factors including voltage, current and pulse width, as indicated by the following table of typical values.

Anode Diameter, mm.	Maximum Voltage, Kv.	Pulse Width, μ sec.	Current, amps.
1.5	105	.03	1,400
2.5	105	.07	1,400
3.8	105	.10	1,400
3.8	150	.07	2,000
6.0	300	.10	1,400
10.0	600	.10	2,000

Of course, the metal window structure 22, 24 and 26 is not essential and this portion of the envelope may be made of glass within which the mounting cylinder 32 is supported on metal pins extending through an envelope in a similar manner to the X-ray tube shown in copending U.S. patent application Ser. No. 114,125 referred to above. In addition, the envelope 12 may be made in any convenient shape and where there is sufficient mounting space, a spherical envelope may be employed to provide more surface for condensation of the anode metal and a longer path for the metal coating evaporated on the inner surface of such envelope in order to extend the lifetime of the tube.

It will be obvious to those having ordinary skill in the art that various changes may be made in the details of the above-described preferred embodiment of the present invention without departing from the spirit of the invention. Therefore, the scope of the present invention should only be determined by the following claims.

We claim:

1. An X-ray pulse generator, comprising:
 - a diode X-ray tube having an evacuated envelope;
 - an anode mounted within said envelope;
 - a field emission cathode mounted within said envelope in spaced, insulated relationship with respect to said anode, said cathode having a plurality of spaced, sharpened emitter portions of sufficiently small radii of curvature to enable the field emission of electrons therefrom and causing said electrons to bombard said anode to emit X-rays from said anode; and
 - pulser means for applying electrical pulses of sufficiently high voltage and high current between said cathode and said anode to initiate the field emission of electrons from at least one emitter portion for each pulse, and to cause some of the material of said cathode to vaporize into positive ions to produce a vacuum arc which greatly increases the current flow in said tube, said anode being sufficiently small and said electrical pulses being of sufficient intensity to cause some of the material of said anode to vaporize when bombarded by said electrons to cool said anode;
- said pulser means including means for forming said electrical pulses with a substantially rectangular waveform and for terminating the electrical pulses before any substantial amount of positive ions of vaporized anode material reaches said cathode to prevent said ions from bombarding the cathode and damaging said cathode.

2. An X-ray pulse generator in accordance with claim 1 in which the anode is of a conical shape.

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3. An X-ray pulse generator in accordance with claim 2 in which the cathode emitter portions are a plurality of spaced needles.

4. An X-ray pulse generator in accordance with claim 2 in which the cathode emitter portions are a plurality of spaced knife edged members.

5. An X-ray pulse generator in accordance with claim 2 in which the conical anode has a maximum diameter of between ten and one millimeter to provide a small X-ray source.

6. An X-ray pulse generator in accordance with claim 5 in which the pulser means causes the electrons to strike the anode at energies above 20 joules/cm.².

7. An X-ray pulse generator in accordance with claim 1 which also includes a tubular shield surrounding said cathode and anode to prevent the vaporized material from being deposited on at least a portion of the envelope.

8. An X-ray pulse generator in accordance with claim

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1 in which both the cathode and anode are made of the same refractory metal.

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