June 30, 1970 W. D. OWEN 3,518,433

METHODS AND APPARATUS FOR GENERATING FLASH X-RAYS EMPLOYING A THREE ELECTRODE FIELD EMISSION X-RAY TUBE

Filed June 19, 1967 3 Sheets-Sheet 1

FIG.1.

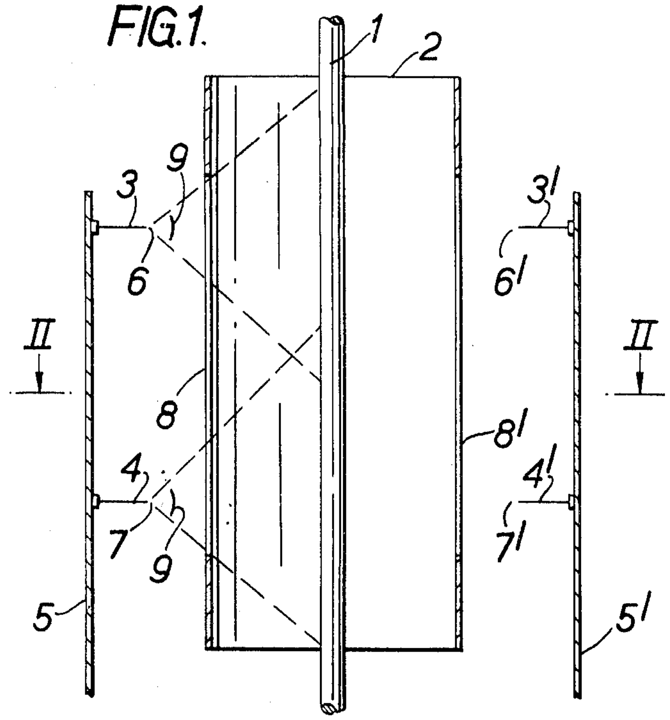


FIG.2.

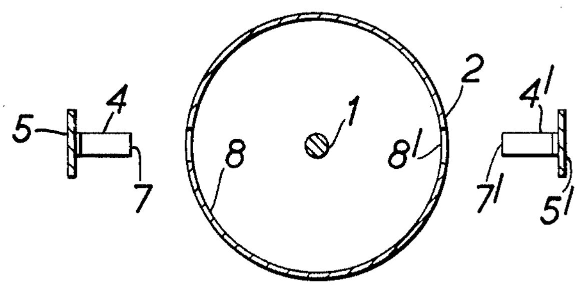
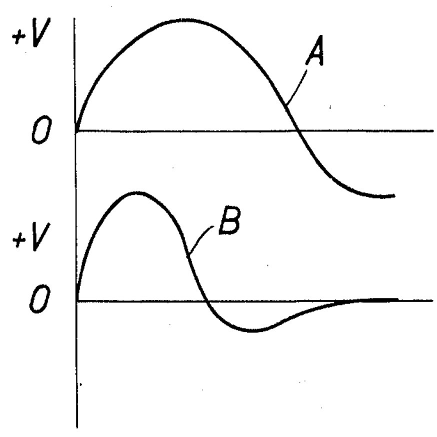


FIG.3.



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3 Sheets-Sheet 2

FIG. 4.

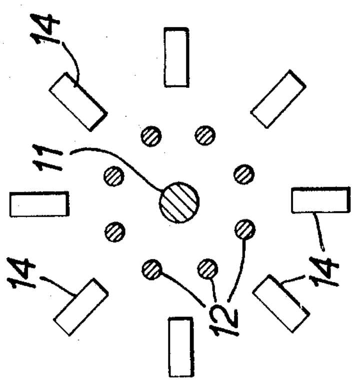
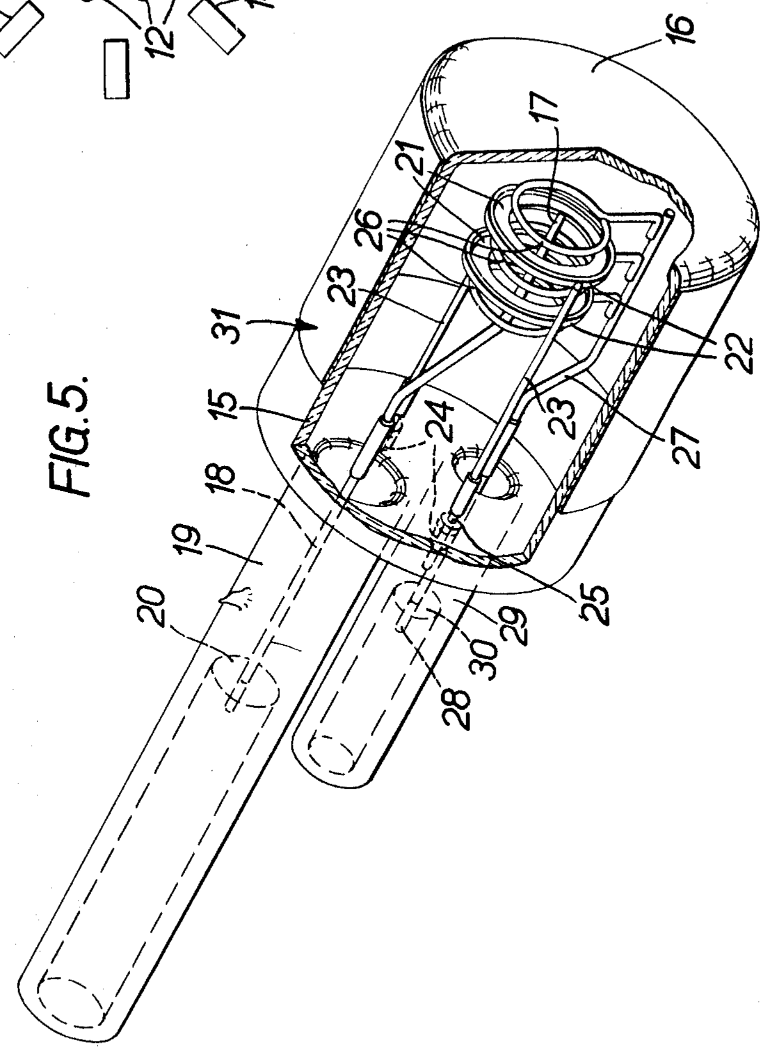


FIG. 5.



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METHODS AND APPARATUS FOR GENERATING FLASH X-RAYS EMPLOYING A THREE ELECTRODE FIELD EMISSION X-RAY TUBE

Filed June 19, 1967 3 Sheets-Sheet 3

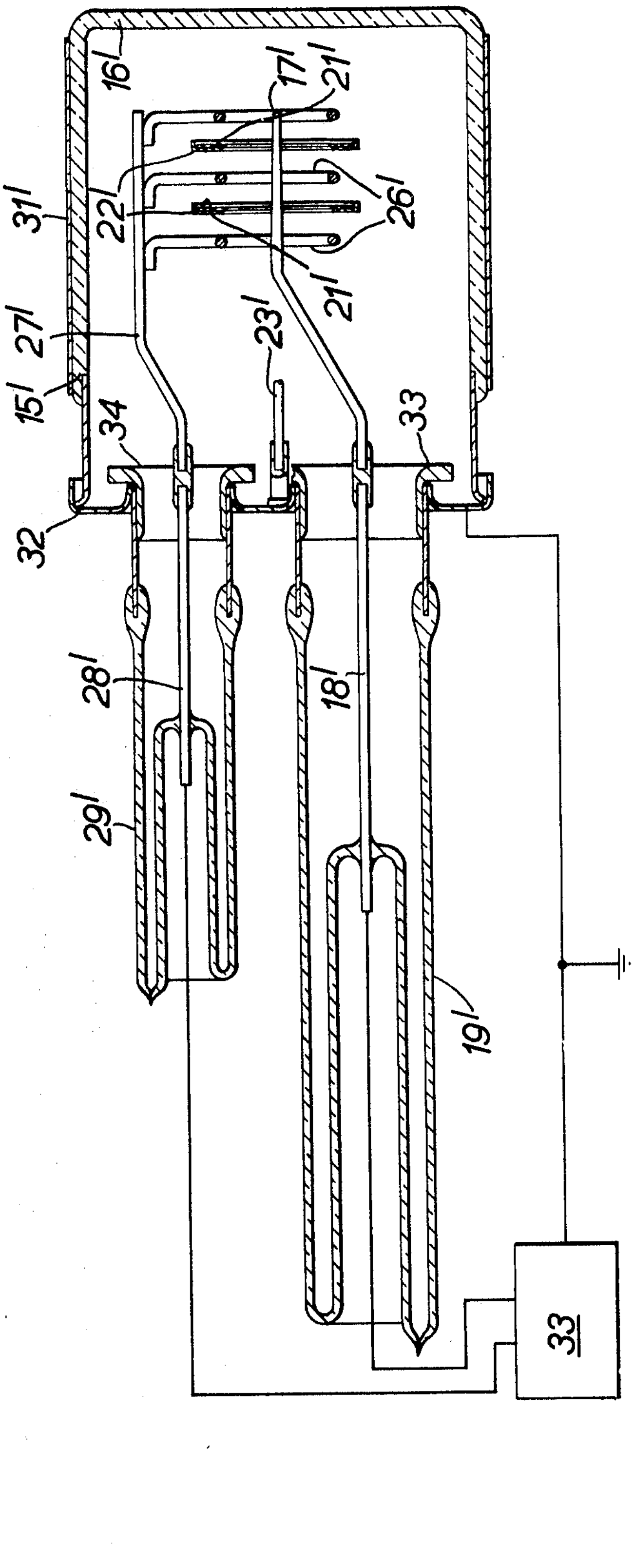

FIG.6.

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METHODS AND APPARATUS FOR GENERATING FLASH X-RAYS EMPLOYING A THREE ELECTRODE FIELD EMISSION X-RAY TUBE

William Denley Owen, Tadley, England, assignor to United Kingdom Atomic Energy Authority, London, England

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Claims priority, application Great Britain, June 22, 1966, 27,896/66
Int. Cl. H05g *1/22*
U.S. Cl. 250—90 13 Claims

ABSTRACT OF THE DISCLOSURE

A method of generating a flash X-ray pulse comprises applying, in a high vacuum, a high voltage pulse between a sharp-edged field-emission cathode and an adjacent control electrode, the vacuum being sufficiently high and the pulse duration sufficiently short to cause electrons to be produced by field-emission from said cathode without subsequent vaporisation of the cathode and formation of a metallic arc, and simultaneously applying a high-voltage pulse between anode and cathode to accelerate electrons emitted from the cathode to generate X-rays at the anode. Advantages include long life, the ability to vary the X-ray energy independently of the X-ray dose, and the ability to tolerate an anode pulse having a negative overswing.

A preferred flash X-ray tube comprises an envelope evacuated to a high vacuum, an anode rod, an annular cathode plate having a sharp inner edge directed towards and coaxial with the anode rod, and a control electrode comprising annular members spaced from each side of the cathode plate at approximately the same radius from the anode as the cathode inner edge.

BACKGROUND OF THE INVENTION

This invention relates to X-ray apparatus and relates in particular to flash X-ray apparatus, in which a short voltage pulse is applied to an X-ray tube to generate a short pulse of X-rays.

Known forms of X-ray tubes used to generate flash X-rays comprise an evacuated envelope containing a target or anode, spaced from a cold cathode having one or more sharp or finely tapered portions from which electrons are extracted by field emission when a positive voltage pulse is applied either to the anode or to a further electrode adjacent the cathode. An example of the former type is described, for example, in British specification No. 987,478, which employs a large number of sharp points as the cathode, and in a high vacuum. The field-emission current is sufficient to partly vapourise the metal of one or more points, thereby producing a metallic arc which provides an enhanced electron current to the anode for the production of the X-rays. An example of the latter type is described, for example, in Proc. I.R.E. 1947, vol. 35, p. 600 et seq. This tube employs an "auxiliary anode" close to the cathode to which a positive pulse is applied coincidentally with the pulse applied to the anode, and a lower degree of vacuum. In this case the initial small field-emission current drawn by the auxiliary anode causes ionisation of residual gas in the tube, and the back-bombardment of the cathode by these ions causes vapourisation of the cathode materials and the production of a metallic arc as before, to provide an enhanced electron current to the anode.

It will be seen that although in both the above types of tubes the initial current is produced by field emission, this mechanism is not relied upon for the required electron current, the latter resulting from the subsequent formation of a metallic arc by vapourisation of the cathode material. The latter process necessarily involves a progressive deterioration of the cathode and hence limits the useful life of the tube. Moreover it is impossible with such tubes to vary the energy of the resultant X-rays (determined by the anode voltage) without simultaneously altering the electron current and hence the X-ray dose.

In the present invention the electron current to the anode is produced solely by field emission, no vapourisation of the cathode material or formation of a metallic arc being involved. The magnitude of the available electron current is largely independent of the anode voltage, and hence the X-ray energy is largely independent of the X-ray dose. Moreover the present invention allows the use of anode pulses having a negative overswing, which would otherwise cause back-bombardment of the cathode (and consequent deterioration) by thermal electrons emitted from the anode as a result of heating by electron bombardment during the positive anode pulse. A pulse generator in which negative overswing of the output pulse is permissible can, in general, be made simpler and cheaper than one in which such overswing must be eliminated.

SUMMARY OF THE INVENTION

According to one aspect of the present invention, a method of generating a flash X-ray pulse comprises applying, in a high vacuum, a high-voltage pulse between at least one sharp-edged field-emission cathode and an adjacent control electrode, the vacuum being sufficiently high and the pulse duration sufficiently short to cause electrons to be produced by field-emission from said cathode without subsequent vapourisation of said cathode and formation of a metallic arc, and simultaneously applying a high-voltage pulse between and anode and said cathode to accelerate electrons emitted from said cathode towards the anode to generate X-rays thereat.

The anode pulse may be a positive pulse having a negative overswing, the pulse applied between control electrode and cathode being a pulse having a positive duration less than the positive duration of the anode pulse.

The target may be a rod, the cathode comprising at least one plate having a sharp edge directed towards said rod and aligned traversely to the axis of the rod, and the control electrode comprising portions spaced from both surfaces of said plate.

Preferably the cathode comprises at least one annular plate coaxial with the rod and having a sharp inner edge, and the control electrode comprises annular members coaxial with said rod and located at approximately the same radius from said rod as the sharp inner edge of the annular plate.

According to another aspect of the present invention a flash X-ray apparatus includes a flash X-ray tube comprising an envelope evacuated to a high vacuum, a sharp-edged field-emission cathode, an adjacent control electrode and an anode mounted therein, pulse-generator means for applying a pulse between said control electrode and said cathode of sufficient power to produce electrons by field-emission from said cathode but insufficient duration to cause vapourisation of said cathode by resistive heating, said vacuum being sufficiently high to prevent vapourisation of said cathode by ion bombardment and said pulse-generator means being adapted to apply simultaneously a pulse between anode and cathode.

The pulse-generator means may provide a pulse between anode and cathode having a negative overswing and a pulse between cathode and control electrode having a positive portion of shorter duration than the positive portion of the anode pulse.

The anode pulse voltage may be variable in amplitude independently of the control electrode pulse voltage.

The present invention also provides a flash X-ray tube comprising an envelope evacuated to a high vacuum and montaining an anode rod, a cathode including at least one plate having a sharp edge directed towards said rod and aligned transversely to the axis of the rod, and a control electrode including portions spaced from both surfaces of said plate.

Preferably the cathode comprises at least one annular plate coaxial with the rod and having a sharp inner edge and the control electrode comprises annular members arranged coaxially with said rod and located at approximately the same radius from said rod as the sharp inner edge of the annular plate.

The vacuum must be at least 10^{-10} torr and preferably at least 10^{-11} torr.

DESCRIPTION OF THE DRAWINGS

To enable the nature of the present invention to be more readily understood, attention is directed, by way of example, to the accompanying drawings, wherein:

FIG. 1 is a vertical section of a simplified flash X-ray tube embodying the present invention.

FIG. 2 is a horizontal section on the line II—II in FIG. 1.

FIG. 3 shows graphs of pulse waveforms suitable for use with the present tube.

FIG. 4 is a horizontal section of a modification of the tube of FIG. 1.

FIG. 5 is a cut-away isomeric view of one preferred embodiment of the invention.

FIG. 6 is a sectional elevation of another preferred embodiment of the invention including connections to a pulse-generator.

FIGS. 1 and 2 show a right cylindrical anode **1**, made of tungsten, surrounded by a concentric control electrode **2** made of tungsten. Outside the control electrode are mounted two pairs of cathodes **3**, **3'** and **4**, **4'** spaced along the anode **1** and mounted on electrically conducing supports **5** and **5'**. Cathode **3** is diametrically opposite cathode **3'**, and cathode **4** diametrically opposite cathode **4'**, the two pairs being arranged in substantially the same vertical plane. These cathodes are made of refractory sheet metal (e.g. tungsten or tantalum) a few thousands of an inch thick which is electrolytically polished by known techniques to give sharp edges **6**, **6'** and **7**, **7'** only a few tenths of a micron in diameter. These edges are arranged, as shown, to lie in planes normal to the plane of the axis of anode **1**. The control electrode **2** is provided with longitudinal slots **8** and **8'** aligned with the cathodes to permit electrons therefrom to reach the anode. It is found that electrons are emitted from the cathode edges with almost uniform density over an angle **9** of about 80°, in a sheet whose thickness is approximately equal to the length of the edges. The longitudinal spacing of the cathode pairs, and the length of the slots, is arranged to give approximately uniform electron density at the anode. The anode diameter is approximately the same as the edge length of the cathodes, the slots being slightly wider.

The above-described assembly is sealed into a glass envelope, omitted for clarity, at a vacuum better than 10^{-10} torr and preferably 10^{-11} or 10^{-12} torr, in order to reduce the formation of ions which would bombard the cathode and cause the edge to vapourise. During the pulse the pressure tends to increase momentarily, returning afterwards to the quiescent value.

In operation a positive voltage pulse is applied between control electrode **2** and the four cathodes, and electrons are emitted therefrom toward the control electrode, passing through slots **8**, **8'**. Simultaneously a positive voltage pulse is applied between anode **1** and electrode **2** (or between anode **1** and the cathodes, as convenient) to accelerate these electrons to the anode and there generate X-rays. As shown in FIG. 3, it is arranged that the accelerating pulse, A in FIG. 3, is of longer duration than the pulse, pulse B, applied to generate the electrons. The rise in temperature of the anode from bombardment by the accelerated electrons causes it to emit thermal electrons but it cools rapidly at the end of pulse B (when the bombardment ceases), and has ceased to act as an effective source of electrons by the time the anode-to-cathode voltage reverses at the end of pulse A. Thus electron bombardment of the cathode is eliminated, or at least reduced to an unimportant level.

For stability of operation, the field applied to the field-emission cathode by pulse B is preferably sufficient to raise the current density (J) at the cathode surface to the space-charge limited plateau which occurs in the region of 10^7 a./cm.^{2}. This plateau is relatively short, and it is a further advantage of the present invention that a constant-amplitude pulse can be used to produce the electrons, thereby enabling the cathode current to be kept in the aforementioned plateau region, while a variable-amplitude accelerating pulse (pulse A) can be applied to produce X-rays of the desired energy at constant dose.

Vaourisation of the cathode edge by resistive heating is prevented by keeping the pulse duration sufficiently short. The heating is proportional to $J\sqrt{t}$, where t is the pulse duration. Suitable values of t are found to be 10^{-7} sec. or less.

To prevent bombardment of the cathode edges by positive ions formed from any residual gas in the envelope or from metal vapour released by the hot target, the duration of the pulses is kept below the transit time of ions travelling between the anode and the cathodes.

In FIG. 1 the principal dimensions are:

	Cm.
Anode diameter	0.2
Control electrode diameter	2.2
Control electrode length	5.0
Diametrical separation of cathode edges	3.2
Longitudinal separation of cathode edges	2.5

Typical approximate operating conditions are:

Total applied voltage (anode to cathode) 100–200 kv.
Anode-to-control electrode—up to $\simeq$ 100 kv.;
control electrode-to-cathode $\simeq$ 100 kv.
Pulse duration (Pulse A) $\simeq 2.10^{-7}$ sec.
Pulse duration (Pulse B) $\simeq 10^{-7}$ sec.
Total peak anode current (four cathodes) 500 a.

Various modifications to this embodiment are possible without departing from its main features. For example the number of cathodes can be reduced to one, or increased to, say, eight; in the latter case two further pairs are preferably opposed on a diameter normal to that of the illustrated pairs.

In the modified form of tube shown in FIG. 4, eight sharp-edged cathode plates **14** are arranged symmetrically about the cylindrical anode **11**, and the apertured control electrode is formed by a grid-like structure of rods **12**.

A cylindrical metallic shield (not shown) may be provided between the cathodes and the glass envelope to prevent any electron bombardment of the latter from causing the release of gaseous impurities. This shield, which is maintained at the cathode potential, also helps to focus the electrons towards the anode. The cathode plates can be attached directly to the shield instead of to the separate supports **5**, **5'**. Instead of using a separate glass envelope, the metallic shield can form part of the evacuated envelope, the connections to the anode and control electrode being made through a glass portion sealed to the shield.

It is possible for the sharp-edged field-emission cathode to be constituted by other than the edge of a plate. For example the radius of curvature of a fine wire can be sufficiently small to enable a length of the wire to function as a field-emission cathode. A wire of 0.0125 mm. (0.0005 inch) diameter may be suitable for this purpose.

DESCRIPTION OF PREFERRED EMBODIMENTS

FIG. 5 is an isometric cut-away view of one form of a preferred embodiment of the invention. It comprises a cylindrical glass envelope **15** having a glass end-window **16** for the transmission of X-rays. A tapered tungsten anode rod **17** is mounted in the centre of the envelope on a Nilo-K rod **18** which is sealed through an extension **19** of envelope **15** at **20**. The tapering improves the axial X-ray yield through window **16** in a known manner. The cathode comprises two tungsten annular plates **21**, coaxial with anode rod **17**, spot-welded to molybdenum annular cups **22** which are spot-welded in turn to two molybdenum rods **23**. The latter are mounted on two Nilo-K rods **24** which are sealed through the envelope at **25**. The control electrode comprises three rings **26** of molybdenum rod of circular cross-section coaxial with anode rod **17** and welded to a molybdenum rod **27** so that plates **21** are equispaced between the rings. Rod **27** is mounted on a Nilo-K rod **28** which is sealed through an extension **29** of envelope **15** at **30**. An earthed Nilo-K shield **31** surrounds the envelope to improve the focussing.

FIG. 6 shows a modified form of the embodiment of FIG. 5 in sectional elevation, using corresponding reference numerals. The assembly of anode, cathode, and control electrode is the same as in FIG. 5, but FIG. 6 shows more clearly the cups **22'** and the annular plates **21'** welded thereto. The plates are of 5 thou (0.125 mm.) tungsten whose inner edge is etched to a thickness of about $\frac{1}{10}$ of a micron. The cups are of 18 thou (0.45 mm.) molybdenum. The rings **26** are of $\frac{5}{64}$ inch (2 mm.) diameter rod and it will be seen that they are spaced from the surfaces of plates **21'** at a radius from anode **17'** approximately equal to that of the inner edge of plates **21'**. The advantage of locating the control electrode at this radius, rather than on a radius closer to the anode as in FIGS. 1, 2 and 4, is that less field-emission current flows to the control electrode during the pulse.

The difference between the embodiments of FIGS. 5 and 6 is that instead of the all-glass construction of FIG. 5, FIG. 6 uses a Nilo-K base-plate **32** sealed to envelope **15'**. The glass extensions **19'** and **29'** are sealed to this base-plate, which also carries stainless-steel anti-corona rings **33** and **34** for the rod connections to the anode and control electrodes. The rods **23'** on which cups **22'** are mounted are omitted for clarity, only the end of one such rod being shown where it is mounted on the base-plate **32**.

In operation the base-plate **32** (or rods **24** in FIG. 5) are earthed and the control electrode and anode pulses (pulses B and A respectively) applied to rods **30** and **20** respectively from a pulse generator **33** (FIG. 6) which can be a Marx-type generator. It will be observed that the anode pulse (pulse A) is applied directly between anode and cathode, and not between anode and control electrode as described with reference to FIGS. 1–4. It is a matter of convenience which arrangement is used, depending on the type of pulse generator, either arrangement being suitable in the present invention. Although the present tube has the advantage of being useable with pulses having a negative overswing, as already described, pulse generators producing pulses without appreciable overswing can be used, such as that described in British specification No. 990,770, in which case the anode and control grid pulses can be of equal length.

Other dimensions in the embodiments of FIGS. 5 and 6 are:

Anode diameter—2 mm. tapering to 1 mm.
Control electrode diameter—2 cm.
Cathode inner edge diameter—2 cm.
Cathode axial separation—1.15 cm.
Control electrode ring axial separation—1.15 cm.
Vacuum—Better than 10^{-11} torr.

Typical operating conditions are:

Total applied voltage, anode to cathode (pulse A)—100–200 kv.
Control electrode to cathode (pulse B)—Up to 100 kv.
Pulse duration (pulse B)—5×10^{-8} sec.
Pulse duration (pulse A)—10^{-7} sec.
Total current to anode—1500 a.

I claim:

1. A method of generating a flash X-ray pulse comprising applying, in a high vacuum, a high-voltage pulse between at least one sharp-edged field-emission cathode and an adjacent control electrode, the vacuum being sufficiently high, the electric field at the cathode sufficiently low and the pulse duration sufficiently short to cause electrons to be produced by field-emission from said cathode without vaporization of said cathode and formation of a metallic arc, and simultaneously applying a high-voltage pulse to an anode to accelerate electrons emitted from said cathode towards the anode to generate X-rays thereat.

2. A method as claimed in claim **1** wherein the anode pulse is a positive pulse having a negative overswing and the pulse applied between control electrode and cathode is a pulse having a positive duration less than the positive duration of the anode pulse.

3. A method as claimed in claim **1** wherein the target is a rod, the cathode comprises at least one plate having a sharp edge directed towards said rod and aligned transversely to the axis of the rod, and the control electrode comprises portions spaced from both surfaces of said plate and located at approximately the same distance from said rod as the sharp edge of the plate.

4. A method as claimed in claim **3** wherein the cathode comprises at least one annular plate coaxial with the rod and having a sharp inner edge, and the control electrode comprises annular members coaxial with said rod and located at approximately the same radius from said rod as the sharp inner edge of the annular plate.

5. A flash X-ray apparatus including a flash X-ray tube comprising an envelope evacuated to a high vacuum, a sharp-edged field-emission cathode, an adjacent control electrode and an anode mounted therein, pulse-generator means for applying a pulse between said control electrode and said cathode of sufficient power to produce electrons by field-emission from said cathode but insufficient amplitude and duration to cause vaporization of said cathode by resistance heating, said vacuum being sufficiently high to prevent vaporization of said cathode by ion bombardment and said pulse-generator means being adapted to apply simultaneously a pulse to the anode to accelerate the electrons thereto.

6. A flash X-ray apparatus as claimed in claim **5** wherein the pulse-generator means comprises means for applying a pulse to the anode having a negative overswing and a pulse between cathode and control electrode having a positive portion of shorter duration than the positive portion of the anode pulse.

7. A flash X-ray apparatus as claimed in claim **6** wherein the anode pulse voltage can be varied in amplitude independently of the control electrode pulse voltage.

8. A flash X-ray tube comprising an envelope evacuated to a high vacuum and containing an anode rod, a cathode including at least one plate having a sharp edge directed towards said rod and aligned transversely to the axis of the rod, and a control electrode including portions spaced from both surfaces of said plate.

9. A flash X-ray tube as claimed in claim **8** wherein the cathode comprises at least one annular plate coaxial with the rod and having a sharp inner edge and the control electrode comprises annular members arranged coaxially with said rod and located at approximately the same radius from said rod as the sharp inner edge of the annular plate and located at approximately the distance from said rod as the sharp edge of the plate.

10. A flash X-ray tube as claimed in claim **8** wherein the vacuum is at least 10^{-10} torr.

11. A flash X-ray tube as claimed in claim **8** wherein the vacuum is at least 10^{-11} torr.

12. A method as claimed in claim **1** wherein the high-voltage pulse applied between said cathode and said control electrode is of such amplitude as to produce a field-emission current density at the cathode surface which lies on the space-charge limited plateau of the current density versus applied field curve.

13. Apparatus as claimed in claim **5** wherein the pulse-generator means comprises means for applying a pulse between said control electrode and said cathode of such amplitude as to produce a field-emission current density at the cathode surface which lies on the space-charge limited plateau of the current density versus applied field curve.

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RALPH G. NILSON, Primary Examiner

C. E. CHURCH, Assistant Examiner

U.S. Cl. X.R.

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