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Barbour et al.

[11] **3,783,288**

[45] **Jan. 1, 1974**

[54] **PULSED VACUUM ARC OPERATION OF FIELD EMISSION X-RAY TUBE WITHOUT ANODE MELTING**

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[52] **U.S. Cl.** **250/414,** 250/417
[51] **Int. Cl.** **H05g 1/32**
[58] **Field of Search** 250/98, 102, 414, 250/417; 313/309

[56] **References Cited**

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3,309,523 3/1967 Dyke et al. 250/102

OTHER PUBLICATIONS

"A 50 Millimicrosec. Flash x-ray Phot. System for Hyervel. Research" Grundhauser et al. Oct. 18, 1960, "Fexitron" Field Emission Corp. Oct. 18, 1960,

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Assistant Examiner—B. C. Anderson
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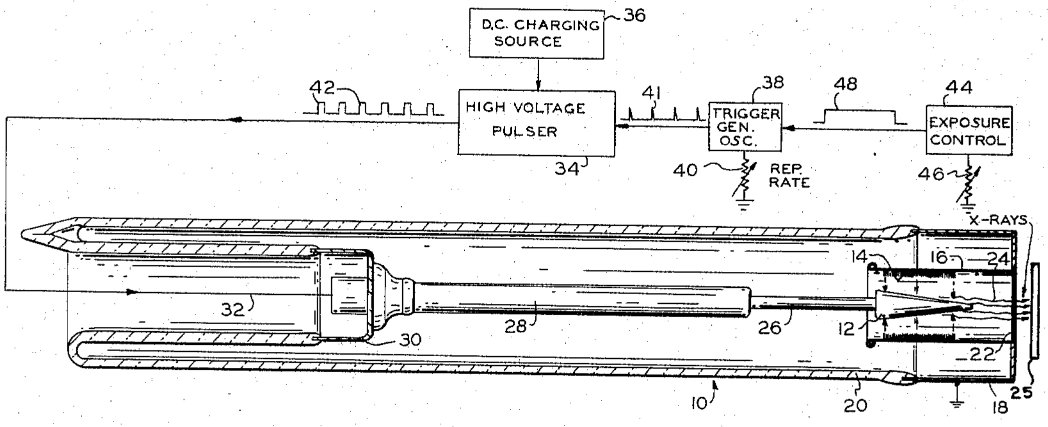
[57] **ABSTRACT**

A field emission x-ray apparatus and pulsed vacuum arc method of operation is described in which a plurality of extremely high voltage pulses of short duration and high repetition rate are applied between the anode and cathode of the x-ray tube to provide an electron discharge of low energy density below about 20 joules per square centimeter to prevent anode melting, which greatly increases the useful lifetime of such tube. For example, with a tube having a conical anode of tungsten having a surface area of 1.8 square centimeter, pulses of 350 kilovolts and 1,000 amperes with a width of 30 nanoseconds, a repetition rate of 1,000 pulses per second can be employed with an energy of 10.5 joules per pulse to provide the tube with a useful life in excess of 200,000 pulses. This increased tube life results from recognition and exploitation of the fact that, at higher pulse voltages, the anode temperature rise per pulse is reduced due to the fact that the electrons penetrate through a thicker surface layer of the anode. The high voltage, greater than about 250 kilovolts, of the pulses also give improved results in radiographic apparatus, such as is employed for x-raying the human chest, since the resulting film radiographs are of better contrast and contain more useful diagnostic information.

12 Claims, 6 Drawing Figures



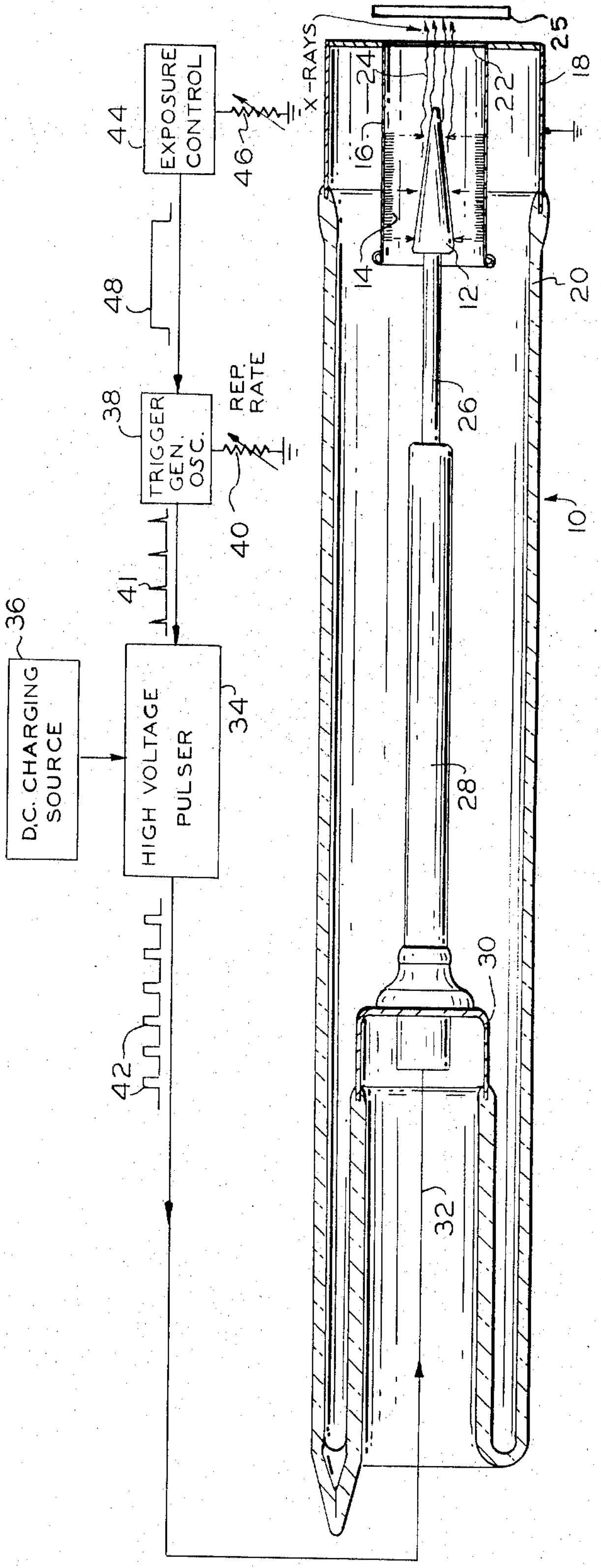

EXPOSURE CONTROL
44
46
X-RAYS
25
18
24
22
16
14
12
20
48
TRIGGER GEN. OSC.
38
REP. RATE
40
26
10
41
D.C. CHARGING SOURCE
36
HIGH VOLTAGE PULSER
34
28
30
42
32

FIG. 1

FIG. 2

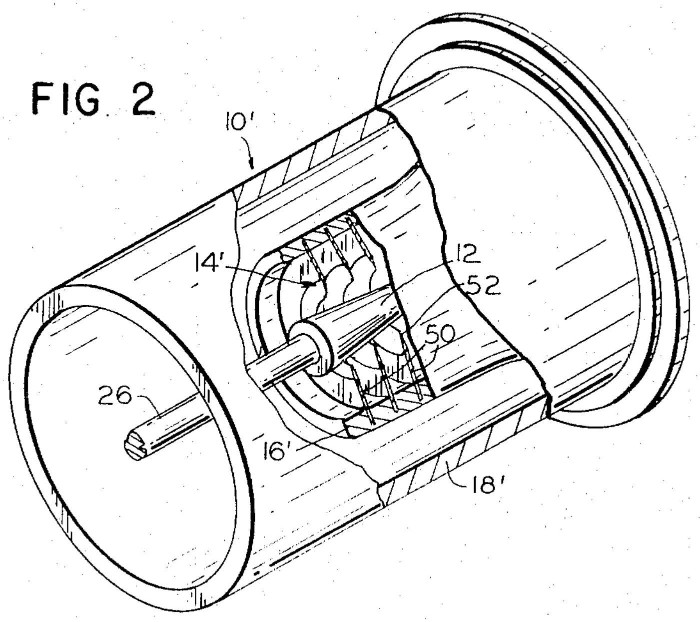


FIG. 3

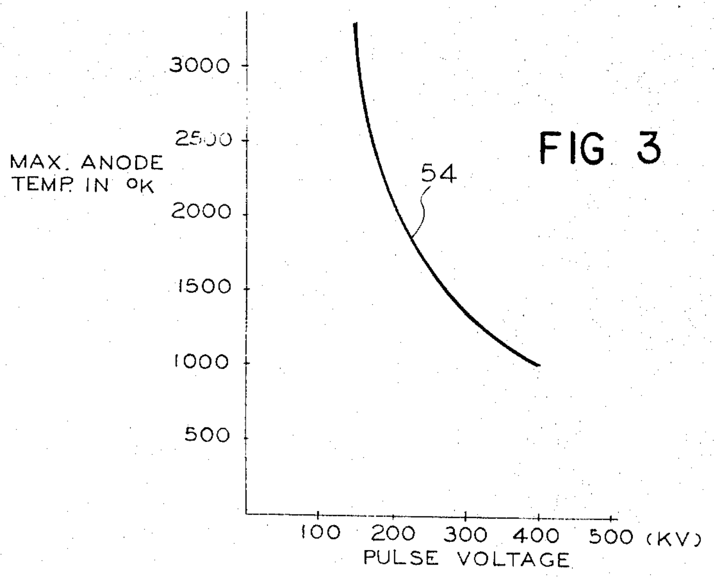
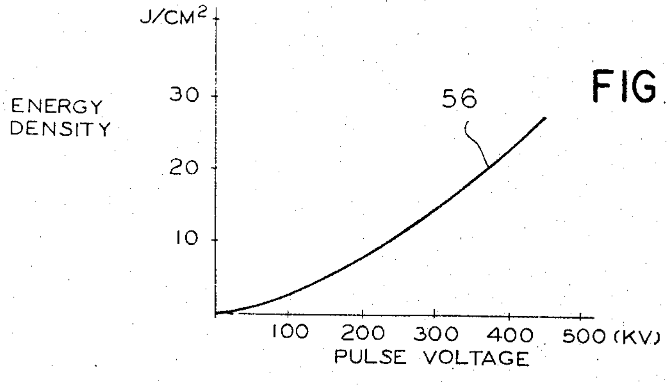


FIG. 4



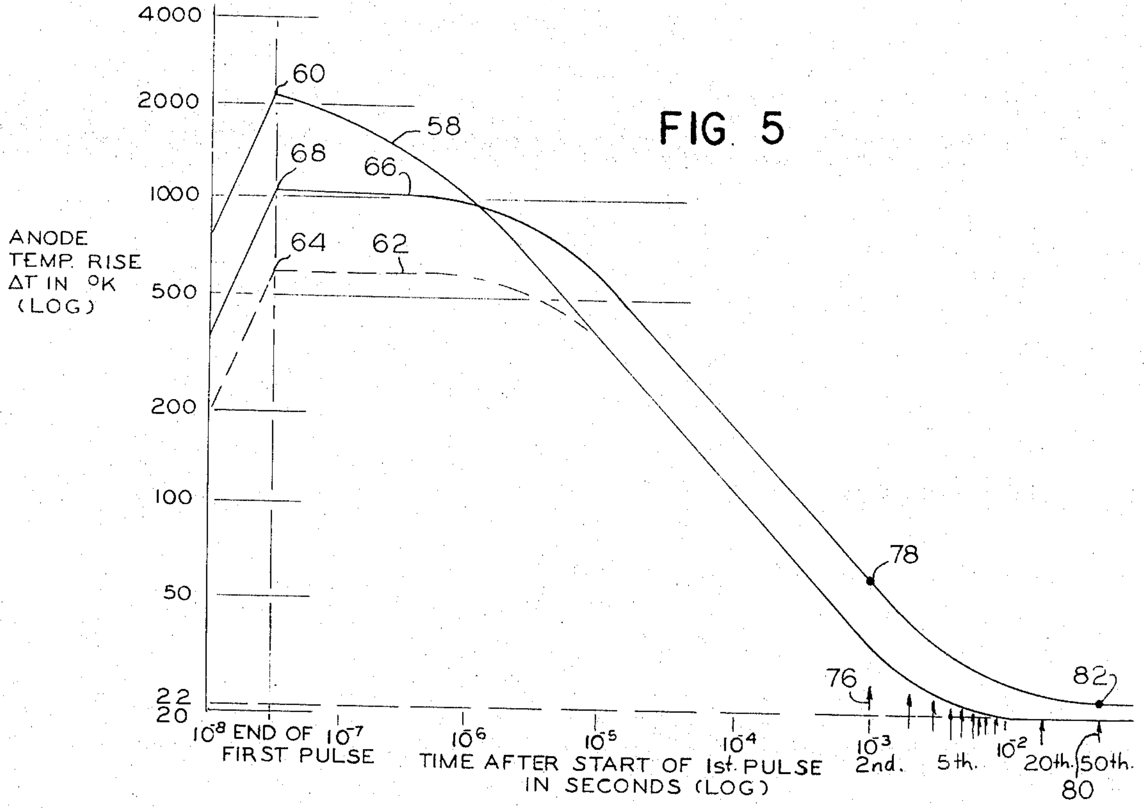


FIG. 5

4000
2000
1000
500
200
100
50
22
20
ANODE TEMP. RISE ΔT IN °K (LOG)
60
58
68
66
64
62
78
76
82
80
10⁻⁸ END OF FIRST PULSE
10⁻⁷
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
TIME AFTER START OF 1st. PULSE IN SECONDS (LOG)
2nd.
5th.
20th.
50th.

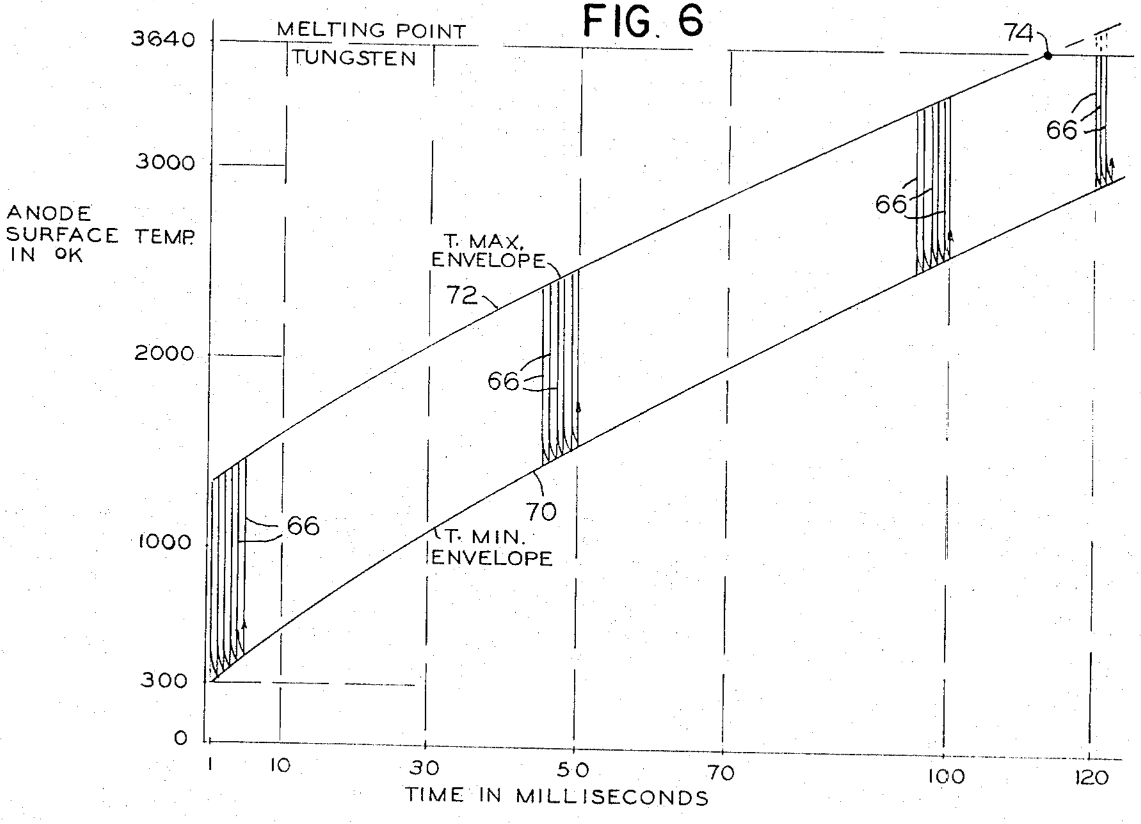


FIG. 6

3640
3000
2000
1000
300
0
ANODE SURFACE TEMP. IN °K
MELTING POINT TUNGSTEN
74
66
66
66
66
T. MAX. ENVELOPE
72
70
T. MIN. ENVELOPE
1
10
30
50
70
100
120
TIME IN MILLISECONDS

PULSED VACUUM ARC OPERATION OF FIELD EMISSION X-RAY TUBE WITHOUT ANODE MELTING

BACKGROUND OF THE INVENTION

The subject matter of the present invention relates generally to pulsed field emission x-ray apparatus, and in particular to such apparatus employing high voltage vacuum arc operation without melting of the anode in order to increase the useful lifetime of the x-ray tube. The x-ray apparatus of the present invention is especially useful as a radiographic apparatus for making radiographs of human chests at high overall voltages of about 300 kilovolts to form radiographs of higher contrast and greater diagnostic information content. However, the present x-ray apparatus may also be employed for industrial x-ray inspection purposes.

Previously, when using pulsed vacuum arc field emission x-ray tubes, high energy electrical pulses on the order of 40 joules per square centimeter have been employed which heat the tungsten anode of such tube above its melting point and causes evaporated cooling of such anode, as described in U.S. Pat. No. 3,309,523 of W. P. Dyke et al., granted Mar. 14, 1967. However, the useful lifetime of x-ray tubes operated in this manner is severely limited. For example, a 300 kilovolt x-ray apparatus manufactured by the assignee of the present invention had a useful x-ray tube lifetime of approximately 1,000 pulses for vacuum arc operation with pulse energies of 70 joules per pulse. In addition, it has previously been proposed to provide a radiographic x-ray apparatus employing a pulsed field emission x-ray tube in which each x-ray exposure is formed by a plurality of short pulses, as disclosed in U.S. Pat. No. 3,256,439 of W. P. Dyke et al. granted June 14, 1966. However, in this prior radiographic apparatus, electrical pulses of lower voltage and lower energy per pulse were employed of, for example, 135 kilovolts and 4 joules in order to prevent destruction of the tube anode, which are not fully satisfactory for chest x-ray surveys since the limited energy per pulse leads to undesirably long exposure time while at the same time the limited voltage leads to excessive x-ray absorption in bony structures, hence to an underexposed low contrast radiograph in several areas, particularly the mediastinum. As a result, several radiographs must be taken from different directions in order to obtain all of the necessary diagnostc information.

It has been found that both of these problems of short tube life and low local contrast radiographs can be solved by increasing the pulse voltage to a value greater than about 250 kilovolts and reducing the energy density per pulse to a value below about 20 joules per centimeter while also controlling the total number of pulses per exposure so that the anode is not heated above its melting point. Thus, one embodiment of the pulsed x-ray apparatus of the present invention operated with pulses of 350 kilovolts and 1,000 amperes, a pulse width of 30 nanoseconds energy per pulse of 10.5 joules, and a pulse repetition rate of 1,000 pulses per second which results in a useful lifetime of the tube of greater than 200,000 pulses and in chest radiographs of excellent overall contrast and high diagnostic information content.

These improved results are achieved, in part, because of the discovery that there is a reduction of anode temperature rise when a higher pulse voltage is used. This is due to the deeper penetration of the electrons into the anode surface. Thus, the tendency of increased heating due to the higher voltage of the electrons is more than offset by the thicker surface layer and correspondingly greater volume of anode material being heated during the pulse. It has been calculated that the depth of electron penetration in the surface of a tungsten anode for a 350 kilovolts pulse is four times that of a 135 kilovolts pulse, while the increase in electron energy for a 350 kilovolts pulse is only 2.6 times that of a 135 kilovolts pulse. As a result, the maximum anode temperature rise is much less for the 350 kilovolts pulse than for the 135 kilovolts pulse. For example, when employing pulses of 135 kilovolts and 4 joules energy with a pulse width of 30 nanoseconds, the maximum anode temperature rise per pulse is approximately 2,150° Kelvin, compared with a temperature rise of only 600° Kelvin for purposes of 350 kilovolts, but otherwise of similar characteristics.

As a result of the reduction in temperature rise, it is possible to increase the energy per pulse to 10.5 joules for the 350 kilovolt pulses and still produce a maximum anode temperature rise of approximately 1,050° K per pulse which is still lower than that for pulses of 135 kilovolts and 4 joules. The maximum temperature at the end of a 50 pulse exposure is still under 3,000° K or well below the melting point of tungsten of 3,640° K even when the temperature rises of such pulses are added to the initial room temperature value of approximately 300° K to determine the final temperature of the anode. Of course, by increasing the energy per pulse, the total number of pulses to provide an adequate exposure is reduced, which is extremely important in chest x-rays to prevent movement of the heart and other organs from "blurring" the radiograph.

It is, therefore, one object of the present invention to provide an improved pulsed field emission vacuum arc x-ray apparatus of longer useful tube life.

Another object of the invention is to provide such an x-ray apparatus in which electrical pulses having a peak voltage of at least 250 kilovolts and an energy of less than 20 joules per square centimeter are applied to the x-ray tube to prevent its anode from being heated above the melting point of the anode material.

A further object of the invention is to provide such an x-ray apparatus as part of an improved high voltage radiographic apparatus for making x-ray radiographs of higher overall contrast and greater diagnostic information content.

Still another object of the invention is to provide such a radiographic apparatus in which each exposure is formed by a plurality of x-ray pulses whose number and repetition rate are such that the exposure time is short enough to prevent motion blur in the radiograph and the maximum anode temperature at the end of the exposure does not exceed the melting point of such anode.

BRIEF DESCRIPTION OF DRAWINGS

Other objects and advantages of the present invention will be apparent from the following description of a preferred embodiment thereof and from the attached drawings of which:

FIG. 1 is a schematic diagram of one embodiment of a pulsed field emission x-ray apparatus in accordance with the present invention with one suitable x-ray tube shown in cross section;

FIG. 2 is a perspective view of another embodiment of an x-ray tube which can be employed in the apparatus of FIG. 1 with parts broken away to show internal structure;

FIG. 3 is a curve showing the maximum anode temperature rise per pulse as a function of pulse voltage, pulse energy and target area being held constant;

FIG. 4 is a graph showing the energy density per pulse required to raise the surface of a tungsten anode to its melting point at different pulse voltages;

FIG. 5 is a curve of anode temperature rise versus time after the start of the first pulse for different pulse voltages and pulse energies; and

FIG. 6 is a curve of the anode surface temperature produced by a plurality of pulses in an exposure pulse train containing pulses identical to those producing the middle curve in FIG. 5.

DESCRIPTION OF PREFERRED EMBODIMENTS

As shown in FIG. 1, one embodiment of the x-ray apparatus of the present invention includes a field emission x-ray tube **10** including an anode **12** of a conical shape and a field emission cathode **14** in the form of a plurality of spaced sharpened needle shaped emitter elements. The field emission cathode needles **14** are supported in four radially spaced groups on a metal support sleeve **16** so that such needles project inward toward the anode. The support sleeve **16** is attached to a metal cup member **18** enclosing one end of the tube envelope and sealed to a tubular glass envelope portion **20** by a suitable glass to metal seal to provide the x-ray tube with an evacuated envelope. A thin x-ray transparent window portion **22** is provided in the bottom of cup **18** in alignment with the anode **12** so that x-rays **24** emitted from such anode are transmitted through such window. When used as a radiographic apparatus, these x-rays **24** are transmitted through the object under investigation, such as a human chest, to expose a film within a cassette **25**. The anode **12** of the x-ray tube is mounted on a stem **26** of reduced diameter which is attached to a support rod **28** extending through another glass to metal seal formed between envelope portion **20** and a metal seal member **30** provided at the other end of the envelope to enable electrical pulses to be applied thereto through lead **32**. X-ray tubes of this construction are known and have been described in the above-discussed U.S. Pat. No. 3,309,523 and 3,256,439 of Dyke et al.

The cathode support cup **18** is grounded and the anode **12** is connected through lead **32** to the output of a high voltage pulser **34** which may be a Marx surge generator but may also be of the Blumlein field reversal type or other high voltage pulser containing storage capacitances. The storage capacitors of the Marx surge generator are charged in parallel and discharged in series through spark gaps. Thus, the pulser **34** is connected to the output of a D.C. charging current source **36** of lower voltage of, for example, about 15 kilovolts. A trigger generator oscillator **38** whose repetition rate is set by the adjustment of a variable resistor **40** is connected at its output to the high voltage pulser **34** for triggering such pulser by trigger pulses **41** which cause the first spark gap to break down. This causes the pulser to produce corresponding high voltage output pulses **42** on conductor **32** of, for example, 350 kilovolts peak voltage and 1,000 amperes peak current with a pulse width of about 30 nanoseconds and a repetition rate of about 1,000 pulses per second. This repetition rate may be varied between about 500 and 4,000 pulses per second, depending upon the setting of resistor **40.** An exposure control circuit **44** including a variable resistor **46** of variable resistance is connected at its output to the trigger oscillator **38** to control the number of trigger pulses **41** and the corresponding number of high voltage output pulses **42** per exposure. Thus, the control circuit **44** applies an enabling signal **48** to the trigger oscillator **38** to cause it to produce trigger pulses so that the duration of the enabling signal **48** determines the total exposure time, and such duration is adjusted by the setting of variable resistor **46.**

As shown in FIG. 2, the x-ray tube **10** of the apparatus of FIG. **1** can be replaced by modified tube **10'** which is similar, but is provided with a different field emission cathode means **14'**. The cathode **14'** is in the form of three or more annular rings **50** having their inner edges **52** provided as sharpened emitting elements which surround the conical anode **12** extending coaxially through such rings. The cathode rings **50** are mounted in a modified support sleeve **16'** so that they project inward and are longitudinally spaced along the anode.

Both the tube **10** of FIG. 1 and the modified tube **10'** of FIG. 2 are provided with a vacuum arc field emission operation in which the electrical pulses **42** applied to the anode cause the field emission of electrons from the sharpened emitter elements of the cathode. These electrons are accelerated by the high pulse voltage to the anode where they bombard the anode surface and cause x-rays to be emitted therefrom. The anode **12** may be made of tungsten or tungsten containing alloy, as well as other refractory metals including molybdenum, and the cathode emitting elements may be made of a similar material. During vacuum arc operation, a portion of the cathode material is vaporized to produce positive ions of cathode material which neutralize the negative space charge ordinarily surrounding the cathode and thereby greatly increase the electron discharge current to provide a current on the order of 1,000 amperes during the brief time period of pulses **42.** This vacuum arc field emission operation produces an intense x-ray pulse of short duration for each electrical pulse **42**, as described in the above-mentioned patents.

As shown in FIG. 3, a curve **54** of the maximum anode temperature rise in degrees Kelvin for different pulse voltages in kilovolts shows that as the voltage increases the anode temperature rise decreases. This is surprising, because one would ordinarily think that the increase in electron energy due to the greater pulse voltage would cause a corresponding increase in anode temperature. However, it has been found that this increase in beam voltage causes the electrons to penetrate through a thicker surface layer of the anode, thereby increasing the effective volume of anode material in which the heat energy is dissipated during each pulse. For example, at 350 kilovolts, the effective depth of penetration of the electrons in a tungsten anode is approximately 17.6 microns, while the effective depth of penetration of electrons at 135 kilovolts is only about 4.4 microns. Thus, it can be seen that the thickness of the anode surface layer in which the heat is dissipated for the 350 kilovolt electron beam is four times that of the 135 kilovolt beam, while the increase in electron energy is only 2.6 times that of the 135 kilovolt electrons. The result is a net decrease in anode temperature with increases in pulse voltage and this decrease in temperature follows along the curve **54** for a pulse energy of 5 joules per square centimeter. This effect is more fully discussed hereafter with respect to FIG. **5.**

FIG. **4** shows a curve **56** of the energy density in joules per square centimeter per pulse at different pulse voltages in kilovolts required to increase the temperature of the tungsten anode surface to its melting point. While the values used in FIG. **4** are calculated values and the actual energy density is lower because of the finite rise time and fall time of the pulse, it can be seen that for a beam of 150 kilovolts, the energy density is about 5 joules per square centimeter to cause anode melting, while at a higher voltage of 350 kilovolts approximately 18 joules per square centimeter are required for melting. Here again, the greater energy density required for anode melting with higher voltage pulses is a result of the increased surface penetration of the electrons which increases the effective volume of anode material available for heat dissipation during each pulse. Thus, the energy density required for melting actually increases with increases in beam voltage.

It has been found that high voltage pulses in the range of 250 to 600 kilovolts, and preferably between about 300 and 450 kilovolts, give greatly improved x-ray radiographs of higher overall contrast and greater diagnostic information content, especially when employed for human chest x-rays. Thus, the x-ray pulses produced at these higher voltages penetrate through the spine and rib bones in the chest to expose organs positioned behind such bones, which is extremely advantageous, especially in the study of the lungs whose outer periphery is frequently hidden in radiograph by the x-ray image of the ribs. It should be noted that at extremely high voltages, greater than 600 kilovolts, x-ray scattering becomes a problem which cannot be solved by conventional Bucky grid type collimators. Previous chest x-ray radiographic apparatus have operated at approximately 150 kilovolts and because of the low contrast several radiographs must be taken from different angles to obtain the same information which can be obtained in a single radiograph taken by a multiple pulse exposure at the high voltage level of, for example, 350 kilovolts in the manner of the present invention.

When a pulsed vacuum arc field emission x-ray tube is operated at this high voltage of about 350 kilovolts and high current of about 1,000 amperes, the tube life is ordinarily severely limited due to melting of the anode. Thus, in one such apparatus manufactured by the assignee of the present application, the tube life was only about 50 pulses. This problem has been overcome in the x-ray apparatus of the present invention by reducing the energy per pulse and increasing the number of pulses per exposure. Thus, it has been found that for voltages greater than 250 kilovolts, the energy density per pulse should be less than 20 joules per square centimeter, and preferably is about 8 joules per square centimeter or less at 350 kilovolts for a typical multiple pulse exposure of 15 pulses or more. Also, the pulses should have a pulse width less than 100 nanoseconds, or preferably about 30 nanoseconds, and a pulse repetition rate greater than 500 pulses per second, or preferably 1,000 pulses per second to give satisfactory exposure time and total energy per exposure without anode melting. Thus, for chest x-rays, the exposure time must be less than about one-fiftieth of a second to prevent motion blur in the radiograph due to, among other things, heart and lung movement. Also, for a normal chest x-ray, a pulse train of approximately 20 pulses of the preferred values given above is sufficient for a proper exposure of about 20 millirads for a patient six feet from the x-ray source when the x-ray cassette **25** contains Kodak RP54 film and two fluorescent intensifier screens on opposite sides of such film.

As shown in FIG. **5,** a curve **58** of anode temperature rise in degrees Kelvin versus time after the start of the first pulse for 135 kilovolt pulses, shows that the temperature rise is a maximum of 2,150° K at peak point **60** corresponding to the end of the first pulse. After the pulse terminates, the temperature rise gradually reduces by heat diffusion into the anode material below the bombarded surface layer to an equilibrium temperature of about 22° K. This curve **58** is for pulses of 135 kilovolts and 4 joules energy with a pulse width of 30 nanoseconds and an effective anode area of one square centimeter. However, a second curve **62** of anode temperature rise versus time for a 350 kilovolt pulse of the same energy and other characteristics shows a peak temperature rise **64** at the end of the first pulse of only about 600° K. Thus, the maximum temperature rise for the 350 kilovolt pulse is over 1,500° less than the temperature rise produced by the 135 kilovolt pulse. This dramatically illustrates the reduction in anode temperature rise resulting from increased pulse voltage that was previously referred to in FIG. **3.** It should be noted that the curve **62** closely follows the curve **58** after the time of 10^{-5} second, since the total energy for both of the corresponding pulses is the same. However, by increasing the amount of pulse energy to 10.5 joules for the 350 kilovolt pulse, a third curve **66** results which has a peak temperature rise **68** at the end of the first pulse of about 1,050° K. This peak temperature rise **68** for the 350 kilovolts, 10.5 joule pulse is still much lower than the peak temperature **60** of the 135 kilovolt curve **58,** even though the third curve **64** is produced by a pulse of over twice the energy. Thus, as a result of the reduction in temperature, it is possible to greatly increase the energy of the 350 kilovolt pulse without causing anode melting, which reduces the number of pulses required for the necessary total exposure energy.

As shown in FIG. **6,** when a plurality of 350 kilovolt, 10.5 joule pulses corresponding to curve **66** of FIG. **5** are applied to the x-ray tube at a repetition rate of 1,000 pulses per second as part of a pulse train, the anode surface temperature increases with each pulse due to the fact that the anode is at some higher temperature and does not cool down to its initial temperature at the beginning of each successive pulse. Thus, when a plurality of 350 kilovolt, 10.5 joule pulses having a repetition rate of 1,000 pulses per second are applied to the x-ray tube, the anode is progressively heated along a minimum anode temperature line **70** corresponding to the envelope of the residual temperature rise at the end of each pulse and along the maximum anode temperature line **72** corresponding to the envelope of the peak temperature **68** of each pulse. It should be noted that the vertical axis of the curve of FIG. **6** is in terms of total temperature in degrees Kelvin, while the vertical axis of FIG. **5** is in terms of temperature rise or change in temperature per pulse in degrees Kelvin. Thus, the minimum anode temperature envelope **70** of FIG. **6** starts at room temperature which is approximately 300° K and the maximum anode temperature envelope **72** starts at 1,050° +300°, or 1,350° K.

An important thing to note in FIG. **6** is that the maximum temperature line **70** does not exceed the 3,640° K melting point **74** of the tungsten anode until after 110 milliseconds. Thus, for the 350 killovolt, 10.5 joule pulses producing the temperature curves **66,** the maximum exposure time without anode melting is 110 milliseconds which corresponds to 110 pulses at a repetition rate of 1,000 pulses per second. As shown in FIG. **5,** on the logarithmic time scale at this repetition rate, the second pulse indicated by arrow **76** occurs one millisecond after the first pulse at a point **78** on the temperature curve **66** which corresponds to a temperature rise of approximately 60° K. Thus, there is a minimum anode temperature increase along curve **70** of approximately 60° K per pulse and a corresponding increase in a maximum temperature curve **72** of a similar amount per pulse. Of course, this is only an approximation because by the time the fiftieth pulse occurs, as indicated by arrow **80,** the temperature curve **56** of the first pulse has decreased to a point **82** of about 24° K. From the above, it can be seen that in order to prevent anode melting which greatly reduces tube life, the total number of pulses per exposure and the pulse repetition rate must be such that the maximum anode temperature line **72** does not cross the melting point **74** of the anode before termination of the exposure. For most chest x-rays, **50** pulses or less will be employed so that there is no danger of this happening when using 350 kilovolt pulses of 10.5 joules energy with a pulse repetition rate of 1,000 pulses per second and a pulse width of 30 nanoseconds in accordance with the preferred embodiment of the invention.

It should be noted that the tube anode on which the temperature curve **66** was calculated had an effective area of 1.8 square centimeters which corresponds to a conical target having a maximum base diameter of 0.2 inch and a cone half-angle of approximately 7° measured between the axis and the side surface of such cone. This provides a small x-ray source having an effective diameter of approximately 3 millimeters which is important for x-ray radiography for good image resolution of small objects.

While the invention has been described with particular reference to medical applications such as x-raying the human chest employing a plurality of high intensity pulses of x-rays, the short duration, high intensity x-ray pulses produced are also particularly useful in high speed cineradiographic systems using either a high speed pin registered framing camera and an x-ray image intensifier with the pulses synchronized with the camera shutter or a high speed film drum. The individual x-ray pulses are preferably less than 50 nanoseconds long so that the system has exceptional stop-motion characteristics for high speed events and pulse rates up to 1,000 frames per second provide excellent slow motion effects. Applications include studies of crash injuries, rocket motors, vibrations, fast moving internal parts, etc.

It will be obvious to those having ordinary skill in the art that many changes may be made in the details of the above-described preferred embodiments 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. Pulsed x-ray apparatus comprising:

an x-ray tube including an evacuated envelope containing field emission cathode means and an anode which emits x-rays;

a high voltage pulse generator having its output connected to said x-ray tube;

exposure control means for triggering said pulse generator and causing it to apply a pulse train containing a plurality of electrical pulses between said cathode and said anode to produce a corresponding number of x-ray pulses during one exposure time period whose duration is determined by said control means, said electrical pulses causing the field emission of electrons from said cathode and the formation of a vacuum arc of vaporized cathode material so that for each electrical pulse said anode is bombarded with an electron discharge of extremely high voltage and high current and emits a corresponding x-ray pulse; and

said electrical pulses having a peak voltage of at least 250 kilovolts and a narrow width so that the anode is bombarded with electron discharge pulses each having an energy density below that causing anode melting and the total number of pulses per exposure and the pulse repetition rate of said pulse train is such as to prevent the anode from being heated to a final maximum temperature above the melting point of the anode material at the end of said exposure period.

2. An x-ray apparatus in accordance with claim **1** in which the anode material contains tungsten.

3. An x-ray apparatus in accordance with claim **1** in which the electrical pulses have a peak voltage between 250 and 600 kilovolts and the electron discharge pulses bombarding the anode have an energy density below 20 joules per square centimeter.

4. An x-ray apparatus in accordance with claim **3** in which the energy density is between 5 and 15 joules per square centimeter.

5. An x-ray apparatus in accordance with claim **1** in which the field emission cathode means includes a plurality of separate spaced sharp emitting elements.

6. An x-ray apparatus in accordance with claim **5** in which the emitting elements are needles.

7. An x-ray apparatus in accordance with claim **5** in which the emitting elements are rings having sharpened inner edges surrounding a conical anode.

8. An x-ray apparatus in accordance with claim **1** in which the pulse rate is at least 500 pulses per second and the pulse width is less than 200 nanoseconds.

9. An x-ray apparatus in accordance with claim **1** in which the anode is made of tungsten, the peak voltage is between 300 and 450 kilovolts, the peak current is 1,000 amperes or more, the energy density of the electron discharge pulses bombarding the anode is 15 joules per square centimeter or less, and the pulse width is 50 nanoseconds or less.

10. A pulsed radiograph method comprising:

producing a pulse train containing a predetermined number of electrical pulses during one x-ray exposure time period, said pulses being of high current of at least 500 amperes and high voltage of at least 250 kilovolts peak voltage;

applying said electrical pulses between a field emission cathode means and an anode of tungsten in an x-ray tube, to cause a plurality of x-ray pulses to be emitted from said anode by a field emission vacuum arc electron discharge operation during said exposure time period;

transmitting said x-ray pulses through an object to form a plurality of x-ray images of said object;

exposing a radiographic film with multiple images corresponding to the x-ray images of said object within said exposure time period; and

controlling the number of pulses in said pulse train, the pulse repetition rate and pulse width so that the anode is bombarded with electron discharge pulses having an energy density less than 20 joules per square centimeter for each pulse and the tungsten anode is heated to a maximum temperature below its melting point.

11. A radiography method in accordance with claim **10** in which said object is an adult human chest, the peak voltage is between 300 and 450 kilovolts and the energy density is between 5 and 15 joules per square centimeter.

12. A radiography method in accordance with claim **10** in which the x-ray exposure is formed by at least 10 pulses having a pulse width of less than 100 nanoseconds and a repetition rate of at least 500 pulses per second.

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