Feb. 23, 1965 L. C. FOSTER ETAL 3,171,030

SYSTEM FOR PRODUCING SHORT PULSES OF X-RAY ENERGY

Filed March 6, 1961 2 Sheets-Sheet 1

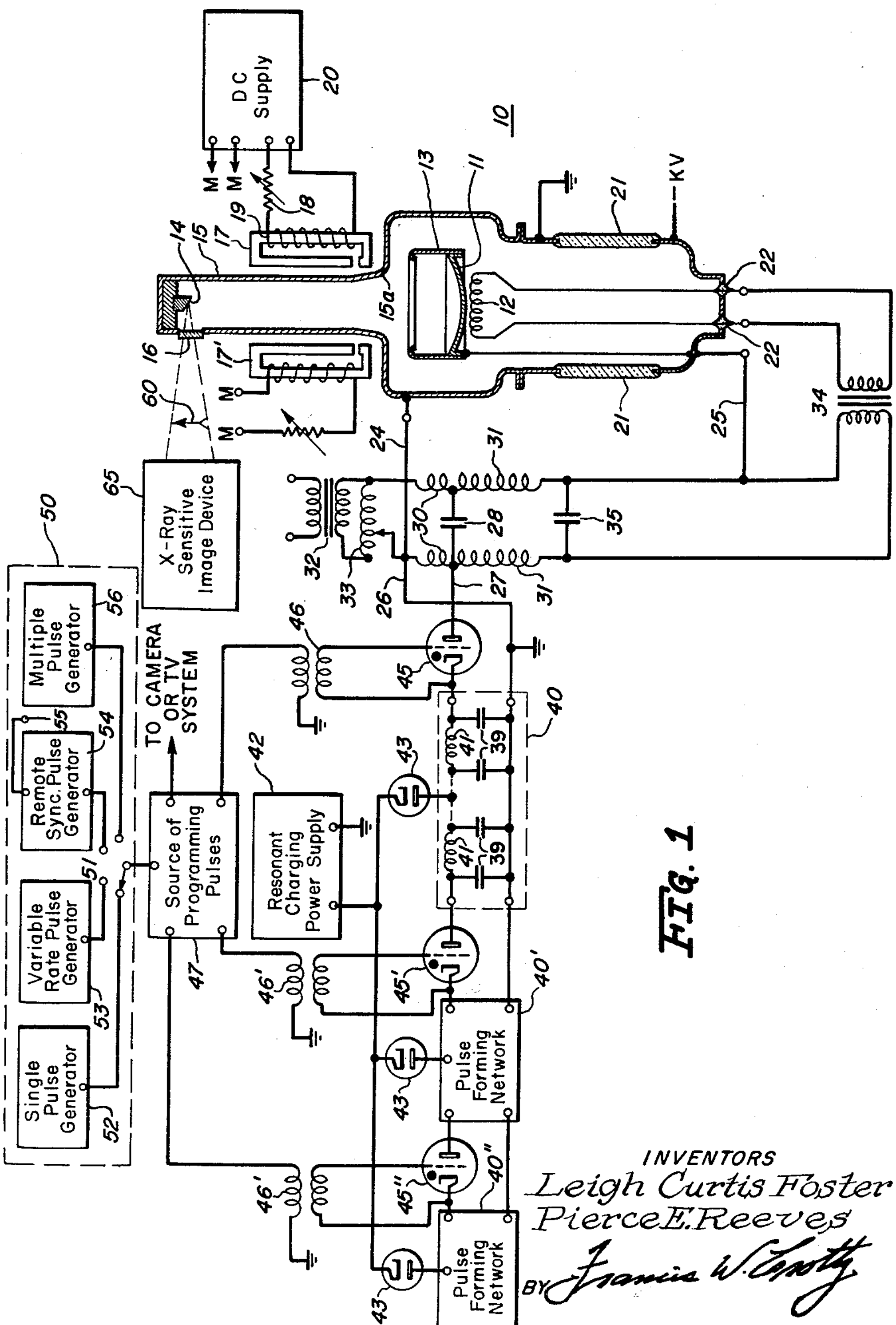

FIG. 1

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FIG. 2

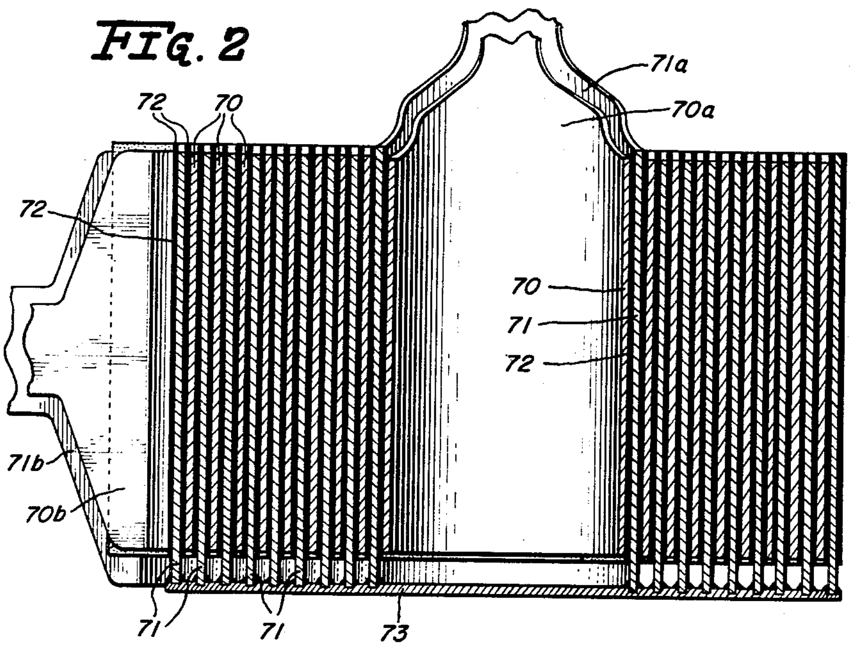
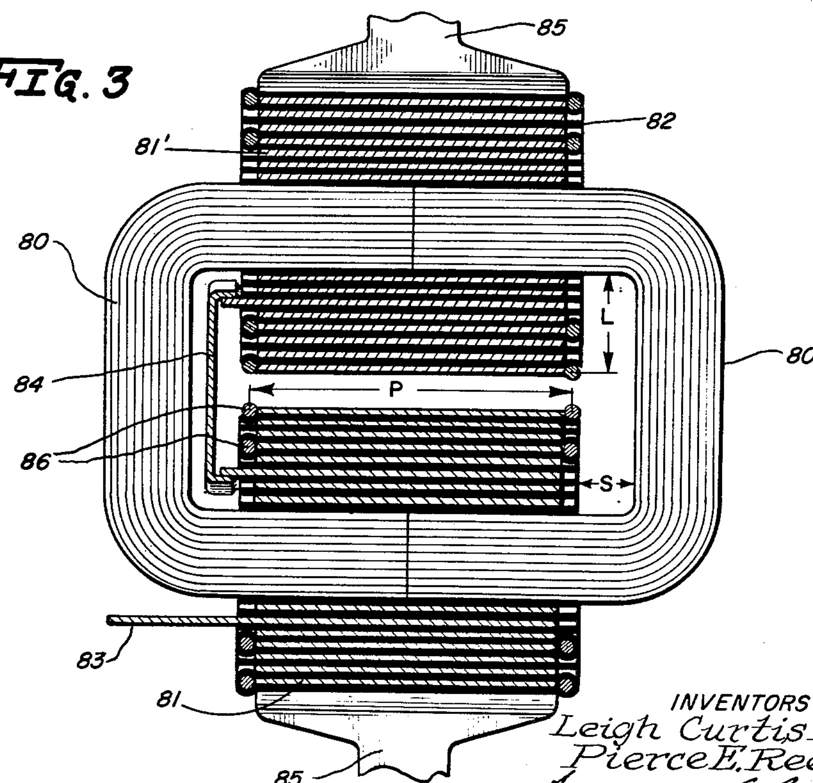


FIG. 3



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SYSTEM FOR PRODUCING SHORT PULSES OF X-RAY ENERGY

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3 Claims. (Cl. 250—95)

The present invention is directed in general to X-ray systems and relates in particular to systems which exhibit great flexibility and therefore lend themselves to a variety of installations.

X-ray systems, of course, have been known for a long time as useful tools for both the medical and industrial fields and it is appreciated that systems of improved versatility are highly desirable because of their increased areas of use. The system to be described herein exhibits great versatility and therefore may more readily satisfy the requirements of widely divergent applications than prior X-ray systems.

For example, the system to be described is especially suited for the production of a series of bursts or pulses of X-radiation of constant and high intensity, each conveniently controllable as to duration and time separation from adjacent pulses. At the same time it is equally suited for production of but a single burst of X-radiation or a series of identical bursts produced on a continuous basis and controllable as to repetition rate. It is expected therefore to have wide application for cineradiography, medical radiology, rocketry, ballistics, crystallography as well as for studies of shock, vibration and radiation effects. Its effectiveness in the taking of radiographic motion pictures of high speed phenomena has been demonstrated repeatedly.

The desirable attributes of this system stem not only from new or improved system concepts but also from the inclusion of newly developed components which are in large measure responsible for the attractiveness of the overall system. For example, the X-ray generating device, which is an unconventional space-charge limited vacuum tube, facilitates the development of bursts of X-rays in accordance with a readily controllable pulse modulation program. The tube structure, per se, is the subject of an application filed concurrently herewith in the name of Leigh Curtis Foster, Serial No. 93,534, which is assigned to the same assignee as the present application.

In order that well defined and constant-amplitude pulses of X-radiation may be produced with preselected duration and easily controllable time separation, the system further includes novel pulse forming networks in the programming or modulating arrangement. These pulse forming networks are associated with a novel high frequency pulse transformer through which a pulse of energy obtained by discharging the previously charged pulse-forming network is stepped up to a value of 100 or more kilovolts for application to the X-ray tube. This transformer facilitates the development of very high energizing potentials with sufficient current capabilities for the tube, yet has a structure of much reduced physical size and weight.

Accordingly, a principal object of the invention is to provide an improved system for the generation of X-rays.

A particular object of the invention is the provision of a novel system for producing short constant-intensity pulses of X-ray energy of preselected duration and readily controllable time separation.

Another specific object of the invention is to provide an improved system for developing constant-amplitude X-ray pulses which may have durations of less than a microsecond in either a single burst or a series thereof at a controllable repetition rate.

Further objectives of the invention are the provision of improved components for an X-ray generating system such as pulse-forming networks and high frequency pulse transformers which impart to such a system attractive operating characteristics.

An X-ray system embodying the invention may produce constant-intensity pulses of X-ray energy occurring with a controllable time separation between successive pulses. The system includes an X-ray generator of the vacuum tube type having a cathode and an anode. A pulse transformer is also provided in the system with its secondary winding connected to the anode and cathode of the X-ray tube. There are a plurality of energy-storage devices individually comprising a pulse-forming time-delay network having a delay corresponding to one-half the desired duration of the X-ray pulse and there are means for charging the networks to store energy therein. A gas-filled trigger tube and the primary winding of the pulse transformer are connected to constitute a discharge path and there are means for completing that path through the pulse-forming networks in a predetermined sequence to discharge the networks individually and with a preselected time separation between the discharge of successive ones of the networks.

In accordance with one aspect of the invention the pulse-forming networks take the form of what may be referred to as a "slab line." It is similar to a transmission line but is formed of a pair of conductors which have a width very much greater than their thickness and coiled together, along with suitable insulation, to form a coiled transmission line section.

Another aspect of the invention features a high frequency pulse transformer through which the slab line may be coupled to the X-ray tube. This transformer is the subject of a divisional application Serial No. 325,678, entitled Pulse Transformer, which was filed on November 22, 1963, and is assigned to the same assignee as the present invention. The transformer preferably is of the balanced type with windings arranged on opposed legs of an O-shaped core. The windings are layer-wound turns of a conductor that is very wide compared to its thickness and corona rings are affixed to certain of the winding turns to protect against the possibility of corona breakdown.

The features of the invention which are believed to be novel are set forth with particularity in the appended claims. The organization and manner of operation of the invention, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings in the several figures of which like reference numerals identify like elements, and in which:

FIGURE 1 is a schematic representation of an X-ray generating system constructed in accordance with the invention;

FIGURE 2 is a sectional view of a slab line employed as an energy storage device in the system of FIGURE 1; and

FIGURE 3 is a sectional view of a pulse transformer connecting such a slab line to the X-ray tube in the system.

Referring now more particularly to FIGURE 1, the system there represented is exceedingly flexible; it may be employed to develop a single burst of X-rays or a sequence of constant-intensity pulses of X-ray energy controlled through a programming arrangement contained in a console which may also house the X-ray generator or even in response to control signals which originate at a remote point. The system includes an X-ray generator **10**, shown schematically and preferably constructed in a manner described and claimed in the above-identified Foster application. Tube **10**, which is of the space-charge limited type, includes a cathode 11 which is a sector of a sphere having an electron emitting oxide surface or coating. A heater 12 establishes the cathode at its operating temperature and a ring type focusing electrode 13, mechanically supported from and maintained at the same potential as the cathode, is provided for initial beam forming purposes. The cathode structure is very much larger in diameter than the portion of the anode structure 15 which includes the target 14 of tungsten or the like.

The anode structure is made of copper and serves as a portion of the tube envelope. In the vicinity of focus electrode 13, the anode flares out to have a generally bell-shaped configuration with its large diameter portion encompassing and in coaxial arrangement with the electron gun of the tube. The shoulder portion 15*a* of the anode structure may be likened to an anode ring which, in conjunction with focus electrode 13, establishes an electrostatic focusing field for focusing electrons issued by cathode 11 into a beam of circular cross section focused on target 14. Target 14 is canted across the electron path to face a beryllium window or exit port 16 through which X-rays are issued to impinge upon a subject under study. The target is conductively connected to and mechanically supported from anode 15 and is therefore at the same operating potential as ring portion 15*a*. This gives rise to a field free space between the target and the anode ring and the tube is dimensioned so that this space is longer than the depth of penetration of any appreciable electrostatic field within the small diameter portion of the anode structure. As explained in the Foster application, this has a distinct advantage in protecting the cathode from tungsten ions which may be emitted as a result of electrons impacting the surface of target 14.

Additional control of the beam configuration as it contacts target 14 is provided by pairs of beam forming magnets disposed adjacent the anode structure between anode ring 15*a* and target 14. A single pair 17, 17′ has been indicated although there may be as many such pairs as desired. Each pair is positioned adjacent the anode structure in diametrically opposed relation on opposite sides of the beam path. The core structure of each magnet has a discontinuity or air gap and the fringing field at the gap penetrates the anode structure in the direction of the beam path. This gives rise to a magnetic lens effect for shaping the beam. Adjustment of the strength of the electron lens results from a control of the ampere turns of the individual magnets. Accordingly, magnet 17 is shown connected to a D.C. supply through a variable resistor 18 connected in series with the winding 19 of the magnet. A like energizing circuit is provided for magnet 17′, having terminals M, M which connect to like designated terminals of D.C. supply 20. It is preferable that supply 20 be of a constant current type because the resistance of the magnet coils may well change due to temperature increase during operation of the tube, especially if the tube is employed to generate a number of pulses with a short time separation between successive ones of the pulses.

The adjustable energization of the magnets permits adjusting the strength and polarity of the field contributed by each and permits ready control of the beam configuration. For many applications, it is desirable that the X-rays appear to emanate from a point source and this result is obtained by shaping the cross section of the beam in relation to the angle of inclination of target 14. The pairs of beam shaping magnets usually change the beam cross section from circular in the region of focus electrode 13 and anode ring 15*a* to a square or linear form on target 14.

Anode structure 15 is maintained at ground potential as indicated and the cathode operates at a negative potential in an amount determined by the desired depth of penetration of the X-rays through the specimen. Segments 21 of the envelope insulate the anode and cathode sections while seals 22 similarly insulate the heater lead-ins. Excitation of the cathode and target or anode of tube 10 is through a balanced pulse transformer having a pair 30 of primary and a pair 31 of secondary windings connected in the fashion of an autotransformer. Leads 24, 25 connect the secondaries of the transformer across the anode and cathode of tube 10 while leads 26, 27 and condenser 28 connect the primaries of the transformer to a modulating or programming arrangement presently to be described. The structural details of pulse transformer 30, 31 are important particularly if the system is to operate efficiently in the generation of constant-amplitude pulses having a duration of the order of a microsecond or less and one form of transformer will be described more particularly hereinafter.

The heater circuit for tube 10 extends through the transformer windings and comprises an isolation transformer 32 having a primary connected to a suitable source of 110 volt A.C. power. The secondary connects to a variable transformer 33 which leads through the balanced windings of transformer 30, 31 to a step down transformer 34. The secondary of this transformer is directly connected to the lead-in conductors of heater 12. By means of a tap on transformer 33 heater wattage may be controlled as required for a particular installation. Condenser 35 is a bypass condenser which bypasses the heater circuit from the high frequency components traversing the transformer in the operation of the system.

The application of excitation potential to tube 10, particularly for the generation of constant-intensity pulses of X-ray energy, results from the discharge of pulse-forming networks, serving as energy storage devices, into autotransformer 30, 31 where the voltage is stepped up perhaps 15 times. Accordingly, the system includes a plurality of such devices 40, 40′ and 40″. Only three such devices are represented in FIGURE 1 but it will be understood that as many are provided as required to meet the needs of a given installation. Preferably, each such device comprises a section of a distributed parameter transmission line as represented within block 40. It has series inductors 41, 41 and interposed shunt capacitors 39, 39. The broken construction lines indicate that the network has as many such L, C sections as required to achieve a desired pulse shape and duration.

The important parameters dictating the make up of pulse-forming network 40 are the duration of the pulse desired, the characteristic impedance of the transmission line section and the energy storage that the section is to represent. The pulse duration is twice the one-way delay of the network and is directly proportional to the square root of the product of the total series inductance and total shunt capacitance. The characteristic impedance is directly proportional to the square root of the ratio of the inductance to capacitance. It should correspond to the impedance of tube 10 as reflected into the primary. As is well understood, the reflected impedance of the tube equals the conductive impedance times $1/n^2$, where n is the number of turns in the step up transformer 30, 31. The characteristic impedance of network 40 should correspond to this reflected impedance of tube 10, as indicated, in order to obtain a condition of impedance matching which assures optimum energy transfer. The specific structure of one form of network, especially suited for the generation of pulses having a duration of one microsecond or even less, will be considered more particularly hereinafter.

Resonant charging of the pulse-forming networks is employed because through that technique the lines may be charged to a potential of nearly twice the potential of the charging source. The resonant charging power supply is designated 42 and usually includes an alternating current potential source connected through a rectifier to an energy storage capacitor and a series inductance to pulse-forming networks to accomplish resonant charging as is well understood in the art. A variac should be connected in circuit with the charging source to permit adjustment of the potential level to which the pulse-forming networks are charged. Such an arrangement in one embodiment of the system successfully operated provided continuous adjustment of the excitation potential of tube **10** over a range from 0 to 150 kilovolts. If desired, one or more of the pulse-forming networks may have an individualized charging circuit so that the relative amplitudes of the pulses of excitation potential may be conveniently adjusted. An isolating stop diode **43** is connected in the charging circuit of each network, being provided effectively to isolate the networks from one another so that one is not able to discharge through another.

A discharge path including a gas filled trigger tube **45** and the primary winding of transformer **30, 31** is provided to facilitate selective discharge of the pulse-forming networks into the transformer. The trigger tube is normally non-conductive and there are means for completing the discharge path through the pulse-forming networks in a predetermined sequence to discharge the networks individually and with a preselected time separation between the discharge of successive ones of the networks. This means comprises a source of trigger pulses utilized to break down trigger tube **45** and successively to break down other trigger tubes **45'** and **45''** through which the pulse-forming networks are connected in cascade. Each trigger tube has a grid or control electrode to which a trigger pulse of positive polarity may be applied to occasion a gas discharge therein. The trigger pulses originate in a generator **47** having output terminals individually connected to the series of trigger tubes **45**. If the trigger tube is a thyratron or ignitron it is generally connected to the trigger source through an isolation transformer **46**.

The details of source **47** of trigger pulses are of no particular concern and therefore have not been shown since such a structure is well known. Preferably, it is a pulse generator which develops a voltage pulse having a duration at least equal to the maximum time separation desired of successive pulses of tube **10** when operated to produce a series of pulses of X-rays. If a trigger pulse applied to trigger **45**, for example, is equal to or nearly equal to the maximum time separation desired of the pulses, the ionization required of tube **45** to permit the successive discharge of the pulse-forming networks therethrough is preserved and the system is freed of the limitation otherwise imposed by de-ionization effects to be explained. Since the pulse-forming networks are to be discharged in a desired sequence, rather than simultaneously, source **47** should represent a plurality of pulse generators or the equivalent in order to present a series of trigger pulses programmed or timed as the installation requires to the series of trigger tubes **45, 45'** and **45''**. Obviously, it is not necessary that source **47**, in fact, have a number of discrete generators; a single generator energizing a time delay network or a series of such networks may be employed to obtain a succession of trigger pulses with a desired time separation between successive ones of the pulses. The internal connections of the generator are, preferably, such that a pulse is applied simultaneously to all of the tubes of series **45, 45', 45''** required to be broken down in order to complete a discharge path from a particular one of the pulse-forming networks to transformer **30, 31**.

It is desirable that source **47** be timed or synchronized to some reference and this may be accomplished by the application of synchronizing pulses from a synchronizing source **50** connected to trigger source **47** through a switch **51**. Source **50** comprehends the application of a single synchronizing pulse, a succession of such pulses occurring at a variable repetition rate, synchronization from a remote source or even timing in response to a finite number of pulses having a very short time separation. Where a single pulse of energy is desired, switch **51** connects a single pulse generator **52** to the synchronizing input of trigger source **47**. Generator **52** can be any form of single shot generator that may be actuated by a manually operated switch or in any other known fashion. Of course, switch **51** is ganged with controllable outputs from trigger source **47** to the end that during intervals in which generator **52** is effective, source **47** provides a trigger pulse to tube **45** only.

A variable rate pulse generator **53** bay be utilized to synchronize trigger source **47** by moving switch **51** to its next contact in a clockwise direction. Generator **53** may be a free-running blocking oscillator or any relaxation oscillator having a controllable repetition rate so that when energized it develops a continuous series of identical pulses of adjustably fixed separation. For free-running or indefinite operation, the time-separation of successive pulses exceeds the charging time constant of of a single pulse-forming network and, therefore, it is only necessary to utilize line section **40** when the programming is under the control of generator **53**. Accordingly, switch **51** through a unicontrol coupling with switches in source **47** causes trigger tube **45** alone to receive trigger pulses. Of course generator **53** may be synchronized in any desired manner.

The third contact of switch **51**, numbered in a clockwise direction, couples a remote synchronizing pulse generator **54** to trigger source **47**. It has an input terminal **55** to which a cable or other connection may be made in order that this generator may be timed from a remote point. The generator may take any of a variety of forms but, in general, should be a device that will generate a single or a known number of pulses of a specified time separation each time a synchronizing signal, originating from a remote point, is applied to input terminal **55**. Again it is assumed that during external synchronizing operation the time separation of successive timing pulses is long relative to the charging time constant of network **40** so for this condition, as with the last two described conditions, only network **40** and trigger tube **45** are utilized.

The last position of switch **51** connects a multiple pulse generator **56** to source **47**. This generator is arranged to produce a finite number, usually five or ten pulses having a timing separation that is shorter than the charging time constant of a single one of the pulse-forming networks. Hence, for this condition the number of line sections **40, 40', 40''** etc. employed corresponds to the number of pulses delivered by generator **56** once it has been excited and, of course, it may be energized manually or from a remote point.

When tube **10** under control of the programming arrangement issues X-rays, they are directed to an object which, for convenience, is shown simply by the arrow **60**. The variation in transmissivity of the object or its outline gives rise to an X-ray image on an X-ray sensitive device **65** which records or makes use of the X-ray image. Unit **65** may likewise take any of a variety of forms. It may simply be a film pack through which an X-ray sensitive film records the X-ray image.

Alternatively, it is very convenient to utilize an X-ray image intensifier for unit **65** which greatly intensifies the X-ray image and converts it into a visible image on a screen in much the same way that a cathode ray tube produces a visible image except that scanning is not required in image intensifiers. In order to attain brightness gain, the image intensifier produces a visual image of reduced dimensions but that image may be enlarged and further amplified by a closed circuit television system focussed upon the image screen of the amplifier.

It is also expected that the X-ray image may impinge upon the target electrode of a camera tube which develops an electrical signal representing the image to energize a video reproducer, obviating the need of an intermediate image intensifier. Both the image intensifier and camera tube have the distinct advantage of introducing gain and therefore decreasing the X-ray dosage otherwise required of the system in order to develop a useful X-ray image. Where unit **65** includes a camera or a television system, it may be timed to the generation of trigger pulses in source 47, being connected therewith as indicated by the legend in FIGURE 1.

In considering the operation of the system, it will be assumed initially that there is need for a single shot or flash of X-ray energy. For this operating condition it is entirely feasible to disconnect all of the pulse-forming networks, except network 40, from the resonant charging supply 42 although the switch required for their disconnection has not been shown. Alternatively, the charging system may be left intact and switch 51 adjusted, as shown, to couple single-pulse generator 52 to source 47 and concurrently to, in effect, disconnect all trigger tubes other than tube 45 from source 47. In short, only pulse-forming network 40 is now operatively associated with X-ray tube 10 and power supply 42 charges this pulse-forming network which is then prepared to excite tube 10 and produce a single pulse of X-radiation.

It will be assumed, of course, that cathode 11 of tube 10 is at operating temperature and that beam forming magnets 17, 17′ have been adjusted to shape the electron beam to the desired configuration on target 14. At this juncture, however, the beam is not energized because thereis no anode-cathode voltage applied to the tube.

When the flash of X-rays is desired, a trigger pulse is developed in source 47, timed by the manually excited single pulse generator 52. The trigger pulse applied to the control electrode of tube 45 creates ionization therein and the tube breaks down to, in effect, connect pulse-forming network 40 directly across the primary winding of autotransformer 30, 31. The network now discharges into the transformer and a voltage is applied from the secondary to the anode and cathode of tube 10. This voltage has a sufficient value to create an electron beam of constant intensity for the duration of the pulse of excitation potential in order to generate a corresponding constant-intensity pulse of X-rays directed to object 60 and recorded in the X-ray sensitive device 65. The excitation potential of tube 10 is of well defined pulse waveform with steep slopes and a flat top because it results from the discharge of pulse-forming network 40 and also because the autotransformer is a high frequency pulse transformer which preserves the wave shape of the pulse. The magnitude of the potential is dictated by the penetration required of the X-rays and may conveniently be adjusted by control of the charging voltage of power supply 42.

Instead of an occasional single pulse, it may be desirable to develop a continuous series of X-ray pulses occurring at some chosen pulse rate. For this case, switch 51 is moved to its next contact to couple generator 53 to source 47. Adjustment of the pulse repetition rate of this generator determines the time separation of successive pulses of X-rays produced by tube 10 and, as explained above, this time separation, even though it is variable, is longer than the charging time constant of pulse-forming network 40. This is the only active pulse-forming network for the condition under consideration and it is successively charged by power supply 42 then discharged across tube 10 in a repeating sequence. Each step in the sequence yields a high and constant intensity pulse of X-rays focused on object 60. This may be likened to a free-running condition which produces a continuous series of such X-ray pulses timed by generator 53.

One highly attractive feature of this mode of operation is its adaptability to cineradiography. A film strip may be positioned to record the X-ray image of the object under observation, either directly or through an intermediate image intensifier and/or closed television system in which case the film records a visible image which is a conversion of an original X-ray image. It is a simple matter to have a film feed mechanism synchronized from generator 53 or source 47 to advance the film one frame after the occurrence of each X-ray pulse. In this manner a continuous film strip may be exposed and may subsequently be projected in the fashion of motion picture film. In one embodiment of the system utilizing a pulse-forming network dimensioned to occasion X-ray pulses of one microsecond duration, pulse repetition rates of as much as 30 per second have been successfully employed in the production of excellent motion picture radiographs.

Either of the aforedescribed modes of operation may be synchronized externally or from a remote point by moving switch 51 to connect generator 54 to source 47. The operation will be much as described above and the same assumptions, as to time separation of pulses in relation to the charging time of the pulse-forming network and as to the utilization of the single network 40, are applicable. One attractive feature afforded by the remote or external synchronization is the possibility of timing the system from a slip-sync unit for slow motion presentation of high-speed motion.

The limitation on the minimum time separation of pulses is imposed by the capacity of power supply 42. For example, if the maximum capability of the power supply is sufficient to support 30 cycles per second with a single pulse-forming network as just described, a larger supply would be required to achieve pulses from the single network occurring with a shorter time separation. Alternatively, and as illustrated in the drawing, a series of pulse-forming networks 40, 40′, 40″ etc. may be used in which case switch 51 is actuated to connect multiple-pulse generator 56 to source 47.

In this condition, all the pulse-forming networks and trigger tubes are effective and source 47 delivers a succession of trigger pulses, perhaps five or ten in number, under the timing or synchronization of generator 56 which imposes on the trigger pulses the desired time separation. The first pulse of this series breaks down trigger tube 45 to discharge pulse-forming network 40 into the autotransformer. This causes the first pulse of X-rays to be developed in tube 10 for application to the object under study.

The second trigger pulse of the series is applied to tube 45 to maintain ionization therein and is also applied to trigger tube 45′ which breaks down and discharges the second pulse-forming network 40′ into the transformer. This network discharges not only through tube 45′ but also through network 40 and trigger tube 45 to occasion the next pulsed excitation of tube 10. Since the duration of the trigger pulse applied to tube 45 is at least approximately equal to the maximum time separation of the pulses of X-ray to be developed, ionization will have been retained in tube 45 as required to discharge network 40′ through network 40 and tube 45. This releases the system from the limitation of the deionization time of tube 45 which otherwise establishes the maximum separation of successive pulses.

The third pulse from source 47 is applied to tubes 45, 45′ and 45″; it ionizes tube 45″ and discharges pulse-forming network 40″ through network 40′, trigger tube 45′, network 40 and trigger tube 45. Of course, the networks employed as energy-storage devices have the same characteristic impedance so the desired condition of impedance matching is maintained at all times in which the X-ray tube is excited. This process continues until the succession of timing pulses from generator 56 has had its full response, assuming that there are at least as many pulse-forming networks as pulses in the series delivered by the generator.

If there are ten pulses in the series, there will usually be ten pulse-forming networks and it may be assumed initially that each results in the production of a one microsecond pulse of X-rays. In considering the free-running condition established by generator 53, an illustrative case was discussed to show that power supply 42 would support a repetition rate of 30 pulses per second from a single pulse-forming network. If the same power supply is used to charge ten such networks, in a period short compared to a second, the charge time required will have been increased ten times but the power supply still supports three multiple discharges of the networks, or a response to three series of timing pulses from generator **56**. It again will accommodate 30 pulses in a second but now the time separation between pulses may be less than the charging time of a single one of the pulse-forming networks. Moreover, the parameters of the individual pulse-forming networks may be selected so that the X-ray pulses of any series have a desired relative duration. That is to say, they may be identical in duration or some may be longer than others. Additionally, their time separation within the series need not be uniform. The time sequence is imposed by and corresponds to that of the sequence of pulses delivered from generator **56**.

The use that is made of the X-rays produced by the system is determined by the particular installation at hand. A photographic X-ray image may be obtained for study purposes in response to single pulse actuation but when the tube is pulse modulated at a repetition rate of 16 to 30 pulses per second, the possibility of radiographic X-ray motion pictures is both real and attractive as already described. Electrical and mechanical components confined within aluminum or steel housings have been subjected to a variety of vibrational forces at rates of from 5 to 5000 cycles per second and their reaction observed by radiographic motion pictures or by radiograph picture sequences produced through the cooperation of a closed television system with the X-ray sensitive image device **65**. This permits, so far as is known, the first possibility of this type component analysis.

The described system in all of its several modes of operation has the distinct advantage of applying essentially square-shaped pulses of excitation potential to X-ray tube **10**. This is in sharp contrast to the sinusoidal excitation potential usually applied in X-ray systems and provides material benefits.

With sinusoidal excitation the anode-cathode potential of the X-ray tube has less than peak value for a large portion of each cycle and this results in the production of soft or low-energy X-rays which is decidedly undesirable. The low-energy rays have very limited penetration and they scatter appreciably in specimens of low atomic number so that their final direction as they emerge from the subject is not accurately representative of their initial direction. This causes smearing and poor contrast in the X-ray image. In medical applications, the low-energy rays result in relatively high radiation damage to the patient since a significant portion of such rays are not able to penetrate completely through the specimen but can cause harmful ionization. It has been the practice in the past to minimize the adverse effects of the low-energy rays by the interposition of attenuating filters. These and similar expedients have some unwanted effects in varying amount on the hard or high-energy rays desired to be used.

It may be shown that the information which can be imaged and recorded from X-radiation is directly proportional to the anode-cathode potential raised to the *nth* power, where *n* has a value between 2 and 5 depending on several factors including the characteristics of the window or exit port material, the cathode emission properties, the characteristics of the X-ray sensitive imaging devices, etc. This further demonstrates that sinusoidal excitation may result in a very substantial change of the total X-radiation in each cycle.

The described arrangement avoids these difficulties and obviates the need for filtering of low-energy rays. It provides hard or high-energy rays substantially independent of time during the excitation pulse and reduces the production of low-energy rays to a minimum. Necessarily, the system efficiency is greater. Of course, these attributes of the system are contributed by the pulse-forming networks which develop the excitation pulse of square wave form in conjunction with the pulse transformer which applies such pulses to the X-ray tube while preserving their waveshape. Illustrative forms of these components of the system will now be discussed.

FIGURE 2 shows a cross sectional view of one form of pulse-forming network referred to as a slab line which is especially suited as an energy storage device for the generation of constant-amplitude pulses in the range from one or more microseconds to less than one-half a microsecond in duration. It comprises a pair of similar flat or ribbon type conductors **70** and **71** having widths that are many times their thickness. Insulating material **72** is interleaved with the conductors and conductors plus insulating material are layer-wound to form a coiled transmission line section exhibiting high unit capacitance and low unit inductance. The values of L and C are important, as explained above, in order to assure the desired condition of impedance match when the pulse-forming network is discharged into transformer **30**, **31** and they are governed by the dimensions and electrical properties of the component parts as well understood in the art. For a rolled slab line of the type under consideration, the pulse length T may be expressed:

$$T=1.69\times10^{-10}l\sqrt{k} \qquad (1)$$

where,

T is duration in seconds
l is the line length in inches
k is the dielectric constant of the insulating material

The impedance Z of such a line is in accordance with the following:

$$Z=188\frac{t}{w\sqrt{k}} \qquad (2)$$

where,

t/w is the ratio of insulation thickness to conductor width.

The problem of impedance match will be appreciated when it is recognized that the impedance of the tube during conduction is of the order of 1000 ohms and a transformer ratio of 15 to 1 may be used for voltage step up purposes. With these representative values, the reflected impedance of the tube into the primary of autotransformer **30**, **31** is of the order of 4 ohms. This low value of impedance is readily satisfied through the slab line construction in which the inductance is made low through the use of very wide conductors and in which the capacitance is made high through the same geometrical considerations of the line structures. One line section constructed for pulse durations of the order of one-half a microsecond employed copper conductors having a thickness in the range of 1 to 5 mils, using mylar or Teflon as the insulation since these materials have an insulating rating in excess of 1 kilovolt per mil thickness. The conductors **70** and **71** have a width of 0.625 inch. The slab line of these specifications utilizing mylar insulation exhibits a delay of 0.1 microsecond per 30 feet of material.

On first inspection, the slab line of FIGURE 2 has striking resemblance to a transformer but transformer action is distinctly undesired. It is obviated by the inclusion of means for short-circuiting coil turns of at least one of the coiled conductors. As shown, a sheet con ductor **73** serves as a short-circuiting bridge between the peripheral portions of convolutions of conductor **71**.

The low inductance property of the slab line is preserved by the provision of low inductance terminal portions through which the line may be connected into the system of FIGURE 1. In general, the desired low inductance of the leads may be realized by using flat conductors in close physical relation which establishes a condition of image currents in the connector pairs at both input and output. For example, one pair of connectors is designated **70*a*** and **71*a*** which extend from the innermost convolutions of conductors **70** and **71**. The remaining connector pair are designated **70*b*** and **71*b*** and they extend from the outermost turns of conductors **70** and **71**, respectively.

A high frequency pulse transformer of the balanced type, suitable for connecting the pulse-forming networks to vacuum tube **10**, is represented in the cross section of FIGURE 3. It has an O-shaped core of a magnetic material, that is, a material having a high permeability at high frequencies such as iron or steel. It is most conveniently formed of two C-shaped sections **80**, **80'** having ground and polished ends abutting one another to define an elongated O. The gap, if any, between abutting ends should be preferably less than one-half mil. The core may be formed of No. 10 silicon steel laminations of 1 to 2 mils thickness.

There are a pair of concentric layer-wound windings on each leg of the core but, since the transformer is connected and utilized as an autotransformer, physically these appear as a single winding **81**, **81'** on each leg. The windings are convolutions of a flat conductor having a width many times its thickness and insulating material **82** is interposed between winding turns. The thickness of the windings represented by dimension L and the width, represented by dimension P, of the winding are dimensioned substantially to fill the opening of the core structure. In one practical embodiment of the transformer, the winding conductor was one mil copper having a width dimension of 2$\frac{3}{16}$ inches with 5 turns constituting the primary and 75 turns constituting the secondary. The insulation was 6 mil thick Teflon having an insulation rating of 500 volts per mil and it was of such width as to extend beyond the winding turns by approximately $\frac{3}{16}$ of an inch at each end. The distance from the end of the winding to the bight of the two C-sections of the core, represented by dimension line S, was ½ inch. When a distributed delay line is used as a pulse-forming network the output voltage is of a potential equal to one-half that to which the line was initially charged. If the line is charged to 20 kilovolts a 10 kilovolt output pulse results. With 10 kilovolts applied to the primary the voltage across the secondary was 150 kilovolts.

In the construction of windings **81**, it is highly desirable to use a very thin flat conductor as described, preferably of 1 to 2 mils thickness in order to accommodate a large number of turns and hence avoid saturation of the core. However, the thinner the conductor the greater is the possibility of corona discharge from the turns which have a high potential relative to the core structure which is usually maintained at ground potential. This difficulty may be avoided by the use of corona rings **86** secured to opposite peripheral portions of certain of the winding turns. Of course, each corona ring must have a larger thickness than the winding conductor and it has been found that lengths of $\frac{1}{16}$ inch diameter wire are suitable for use as corona rings.

A low inductance lead **83** connects to the primary of winding **81** and, through a low inductance strap **84**, this conection is extended to primary winding **81'**. Terminal connectors **85**, formed of flat ribbon conductors, extend from the secondary windings of the transformer for connection to a load such as X-ray tube **10**.

The described transformer is a high frequency pulse transformer that has distinct advantages over predecessor structures. It is very effective in translating pulses having a duration in the order of a fraction of a microsecond to one or more microseconds from the pulse-forming networks of FIGURE 1 to the X-ray tube **10** while preserving their wave form. A one micosecond pulse has a fundamental component at 500 kilocycles and, assuming it to be rectangular in shape, harmonics thereof up to perhaps the tenth and preferably the twentieth. The passband of the transformer, in order to translate such a pulse while preserving its shape, extends up to the highest harmonic desired and its phase shift char-

acteristic is substantially linear over than band. The dimensions of the core are as follows:

	Inches
Overall length	7½
Overall width	5½
Internal length	3½
Internal width	1½
Depth	1⅞

The transformer of these specifications has a weight of 12 to 15 pounds whereas prior art structures of the same electrical specifications weigh in the order of 75 pounds. The volume of the described transformer is approximately 300 cubic inches which is in sharp contrast to the 2000 cubic inch volume of typical prior art transformers.

While a particular embodiment of the invention has been shown and described, it will be obvious to those skilled in the art that changes and modifications may be made without departing from the invention in its broader aspects, and, therefore, the aim in the appended claims is to cover all such changes and modifications as fall within the true spirit and scope of the invention.

We claim:

1. A system for producing short pulses of X-ray energy occurring with a controllable time separation between successive pulses comprising:
   - an X-ray generator of the vacuum tube type having an anode and a cathode;
   - a pulse transformer having a primary winding and having a secondary winding connected to said anode and cathode;
   - a plurality of pulse-forming time delay networks each exhibiting a delay corresponding to one-half the duration of the pulse derived therefrom;
   - uni-directional potential means for charging said networks to store energy therein;
   - a like plurality of controllable firing devices individually associated with respective ones of said networks and together therewith constituting a series circuit coupled to the primary winding of said transformer by one of said devices;
   - and means for controlling said firing devices to establish a discharge path through said networks in a preselected sequence to discharge said networks individually and develop a series of pulses having predetermined time separations therebetween, said time separations determined in part, by the delay times of said networks.

2. A system for producing short pulses of X-ray energy occurring with a controllable time separation between successive pulses comprising:
   - an X-ray generator of the vacuum tube type having an anode and a cathode;
   - a pulse transformer having a primary winding and having a secondary winding connected to said anode and cathode;
   - a plurality of pulse-forming time delay networks each exhibiting a delay corresponding to one-half the duration of the pulse derived therefrom;
   - uni-directional potential means for charging said networks to store energy therein;
   - a like plurality of gas filled trigger tubes individually associated with respective ones of said networks and together therewith constituting a series circuit coupled to the primary winding of said transformer by one of said tubes;
   - and means for triggering said tubes to establish a discharge path through said networks in a preselected sequence to discharge said networks individually and develop a series of pulses having predetermined time separations therebetween, said separations determined, in part by the delay times of said networks and
   - said last-mentioned means including means for maintaining a condition of ionization in said one tube for

a period at least equal to the maximum time separation between the discharge of said networks.

3. A system for producing short pulses of X-ray energy occurring with a controllable time separation between successive pulses comprising:

an X-ray generator of the vacuum tube type having an anode and a cathode;

a pulse transformer having a primary winding and having a secondary winding connected to said anode and cathode;

a plurality of pulse-forming time delay networks each exhibiting a delay corresponding to one-half the duration of the pulse derived therefrom;

uni-directional potential means for charging said networks to store energy therein;

a discharge path including a like plurality of gas filled trigger tubes each having a control electrode and individually associated with respective ones of said networks and together therewith constituting a series circuit coupled to the primary winding of said transformer by one of said tubes;

and means for selectively applying trigger pulses to said control electrodes to establish a discharge path through said networks in a preselected sequence to discharge said networks individually and develop a series of pulses having predetermined time separations therebetween, said time separations determined, in part, by the delay times of said networks and

said last-mentioned means including a pulse generator for applying to said control electrode of said one tube a trigger pulse having a duration at least equal to the maximum time separation between the discharge of said networks.

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