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NEW SOURCES OF X RAYS

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CONTENTS

THE year 1970 was the seventy fifth anniversary of the discovery of x rays—one of the most remarkable achievements of the experimental physics of the past century. The enormous influence of this discovery on the development of twentieth-century physics, as well as on medical diagnostics, radiation genetics, radiation therapy and other fields of science and technology is generally recognized.

The extensive utilization of x rays in various physical and applied problems has stimulated the continuous perfecting of the existing and a search for new sources of this radiation. During the first two decades (1885–1915) the x-ray sources utilized in physics and medicine differed little in working principle from the tubes proposed by Roentgen himself. These were gas-discharge devices operating on the left branch of the Paschen curve at residual gas pressures of about 10^{-3} Torr. The source of fast electrons in such tubes was the cathode bombarded by positive ions in the gas discharge. The chief shortcomings of these tubes were the lack of constancy of their characteristics and the difficulty of separate control of the current and of the voltage.

In 1914 Coolidge proposed and constructed a high-vacuum x-ray tube with an electron source in the form of an incandescent tungsten cathode. The cathode temperature determines then uniquely the emission current and the voltage applied to the vacuum space determines the energy of the electrons. During the past half a century tubes with hot cathodes have been the principal sources of x rays in the most varied fields of physics, medicine, and technology. A large number of various modifications of such tubes have been made from devices operating at voltages of several tens of kilovolts for surface radiation therapy and x-ray structure analysis of materials to large sectioned tubes for several megavolts used in radiation therapy and x-ray flaw detection in bulky items.

Limitations connected with the permissible temperatures and size of the cathode surface, as well as with the space charge of the electrons, do not make it possible to obtain large electron currents in x-ray tubes with incandescent cathodes. As a rule they do not exceed several tens of amperes. Therefore, for physical and technological problems requiring particularly powerful sources of x rays pulsed devices with x-ray tubes utilizing the phenomenon of field emission have been developed and have acquired independent significance. The electron currents in such generators lie within the limits of 10^3–10^6 A and the peak power can reach 10^{12} watt.

In addition to large installations for obtaining very intense flashes of hard x rays, during the past decade tubes with field-emission cathodes have began to be utilized in miniature portable pulsed x-ray units. The absence of sources for supplying the tube heating and the decrease in the dimensions of the elements for pulsed high-voltage operation made it possible to produce a setup for a voltage of 150–300 kV weighing no more than 30 kg, and in certain cases only a few kilograms. These instruments found use not only in special physical investigations but also in x-ray flaw detection and in medical diagnostics.

In this article we consider the present-day state and features of the application of pulsed sources of x rays making use of the phenomenon of field emission. We do not discuss in the review three-electrode pulsed x-ray tubes with "priming" at the cathode. Such devices which gained considerable currency in the Forties and Fifties are now being displaced by the simpler two-electrode systems. We considered it useful to include in the article information on the methods of generation of short flashes of x rays in pulsed discharges in air as well as in hydrogen and other gases at low pressures. Although devices making use of the excitation of x rays of discharges on the right branch of the Paschen curve and near its minimum have so far not seen appreciable practical application, this direction in the development of methods of generation of x rays appears, undoubtedly, promising.

The last section of the review contains brief information on radioactive sources of characteristic x rays and low-energy (4.5–100 keV) gamma rays. In spite of the relatively low intensity of the radiation of such sources, they have recently found increasing application in various physical investigations and technical problems.

1. PULSED X-RAY SOURCES WITH FIELD EMISSION

Experimental and theoretical investigations of field emission have made it possible to reveal a number of physical properties which determine the utilization of this phenomenon for practical purposes. The emission of considerable electron currents in electric fields $\sim 10^7$–10^8 volt/cm without cathode heating, the large slope of the current-voltage characteristic, the possi-

bility of obtaining high current densities (up to 10^8 A/cm^2) provide advantageous differences between field emission and thermoemission cathodes and ensure simplicity of construction and economy of devices with field-emission cathodes.

It follows from the Fowler-Nordheim formula that to obtain stable field emission one must stabilize the electric field intensity (the dimensions and shape of the emitter, the voltage across the gap) and the work function of the field-emission cathode. In practice this is connected with a number of difficulties which were considered in the work of Dyke and Dolan,[1] Elinson,[2,3] Martin et al,[4] and van Oostrom.[5] Emitters are usually prepared using refractory metals or alloys by electrochemical etching of wires down to final radii of curvature between tens of angstroms and several microns. Individual points are welded into "combs" or "carpets." In order to insure the simultaneous operation of numerous points, their radii of curvature are stabilized, in accordance with the proposal of Dyke et al.,[6,7] by heating in an ultrahigh vacuum. The stabilizing of the electrical fields on the emitters in the work of Dyke[6] and Charbonnier et al.[8] is also carried out by a "field evaporation"—by keeping the emitter at a positive potential with a high field intensity ($E \sim 10^8$ V/cm). Single emitters, "combs," and "carpets" can be utilized in an ultrahigh vacuum after careful outgassing of the entire instrument. Infringement of these conditions leads to deformation of the points during operation due to ion bombardment, as well as to a change in the work function when gases and vapors are adsorbed on the surface of the field emitter. Both of these destroy the stability of the field-emission current.[4,5] At a pressure of $P \simeq 10^{-6}$ torr stable operation of a point cathode is only possible with continuous heating of the cathode up to $\sim 1800^\circ$C.[6]

The extreme case of current instability is electrical breakdown between the cathode and anode, which usually leads to melting of the point and renders it inoperable because of the sharp increase of its radius of curvature. Investigations of the breakdown mechanism under conditions of ultrahigh vacuum are given in articles by Dyke,[9,10] Dolan et al.,[11] Furseĭ and Vorontsov-Vel'yaminov,[12] and in other papers. For large emission current densities of the thin points of the cathode are heated up by Joule heat, and thermal field emission appears. This leads to further heating of the point, a current increase, an explosion-like evaporation of the emitter, and the development of electrical breakdown in the metal vapors of the cathode point.

When the outgassing of the field-emission device is insufficient, the breakdown voltage of the vacuum gap with a sharp cathode is appreciably lower. The process of the appearance of breakdown under such conditions becomes more complicated by the participation of atoms and ions separating from the parts of the tube under the action of electron bombardment.[2] Jones and Morgan[13] and other authors[2,14] indicate that the decrease of the breakdown voltage can also be connected with sparking at the dielectric inclusions on the cathode surface under insufficiently clean experimental conditions.

In comparing the data on electrical breakdown in high vacuum it was possible to discern the possible regions of existence of various mechanisms of vacuum breakdown as a function of the time of operation of the voltage and the degree of conditioning of the electrodes.[15] A decrease in the duration of the electric pulse and a lowering in the pressure of the residual gases (the amount of adsorbed matter on the electrodes) lowers the probability of vacuum breakdown and decreases the number of possible mechanisms. In ultrahigh vacuum the usual cause of breakdown is field emission, even in the case of close to uniform fields. The same processes are most probable for breakdown with short voltage pulses ($\tau < 10^{-7}$ sec) independent of the degree of conditioning of the electrodes. Instabilities related to cathode sputtering are also less probable for short applications of the voltage to the electrodes. For this reason field emitters came to be particularly extensively used in x-ray tubes operating with short voltage pulse.

Extensive investigations and developments in this field were carried out by the American firm "Field Emission Corporation."[1,4,6-11,16-22] This firm produces a series of electrovacuum devices in which the electron sources are pointed tungsten cathodes. The technique of pumping down without oil to a gas pressure of $\sim 10^{-12}$ Torr, the use of high-purity materials and of special glasses, and the utilization of short voltage pulses ensured adequate stability and satisfactory service life of the devices with field emission cathodes.

Generators of x-ray flashes, Fexitrons, and sources of fast electrons, Febetrons, utilize cathodes in the form of multipoint emitters. In high-power operation the current is generated by field emission, evaporation, and ionization of the vapor of the metal cathode.[16,17] The high-voltage pulsed breakdown is interrupted until the discharge goes over into the arc phase. The duration of the high-voltage pulse is shorter than the time of flight of an ion between the cathode and anode.[18] Similar discharge phenomena can destroy one or more points during each pulse. However, a sufficient number of points on the cathode ensures a large number of operations.[16] Depending on the purpose of the device, Field Emission Corporation operates in the voltage range of 100—2000 kV. The currents in pulsed x-ray tubes and sources of fast electrons are in the range of 1—10 kA, the duration of the flash is 3—100 nsec, and the dimensions of the focal spot are 0.5—9.5 mm. The dose power in the plane of the window can according to the data of Dyke, Charbonnier et al.[19,20] reach 2×10^{11} r/sec working with an x-ray tube and 2×10^{15} r/sec in the emission of fast electrons. Similar characteristics of Fexitrons and Febetrons produced by this firm are given in[19-23] as well as in the patents and sales literature.

In the Soviet Union studies of the theory of field emission and the experimental verification of a series of laws accompanying this phenomenon were carried out by M. I. Elinson, G. N. Shuppe, I. L. Sokol'skaya, G. N. Furseĭ, V. N. Shrednik, G. A. Mesyats, and others. Most of the experiments were carried out in ultrahigh vacuum. However, unlike in the firm Field Emission Corporation, pulsed x-ray tubes with field emission were constructed to operate at residual gas pressures of 10^{-6}—10^{-7} Torr without the use of specially prepared tungsten point field-emission cathodes. At voltages of 1.5—2 MV the electric fields of 10^{-7}—10^{-8} V/cm essential for appreciable field-emission currents can be ob-

tained on a cathode in the form of a tube with sharpened edges. The microrelief of such relatively roughly processed cathodes ensures large field-emission currents during the initial stage of the electric breakdown which goes over subsequently into a low-voltage discharge in the metal vapors and gases. The time between the beginning of the field-emission current and the appearance of the low-voltage discharge determines in this case the duration of the x-ray flash. Depending on the capacitance and inductance of the supply and on the amplitude of the voltage pulse, the pulse duration lies within the limits of 150—600 nsec.

Characteristic representatives of such devices are pulsed x-ray tubes with a needle shaped anode. Their development was started by Tsukerman and Manakova in 1948 and continued in the work of Zyuzin,[25] Tarasova, and others.[26] In spite of the lack of the required focusing of the electrons, for such an electrode geometry the actual projection of the focal spot in a plane perpendicular to the tube axis for beams of small divergence is circular with a diameter close to that of the tungsten needle (2—4 mm).

The devices for obtaining microsecond and nanosecond x-ray flashes were initially intended mainly for the study of rapidly occurring phenomena (explosions, experimental gas dynamics, ballistics problems). In order to obtain sharp shadow photographs under such conditions, it is necessary for the x-ray flash to be shorter than the time interval during which the image of the investigated object is displaced by tenths of a millimeter in the plane of the photograph. A technique was developed for obtaining two, four, and eight successive x-ray photographs of the same phenomenon with given time intervals between the "frames."[24] Along with these applications, field-emission tubes and the methods of pulsed x-ray photography came to be used in the x-ray structural analysis of rapidly changing structural transformations.[27,28]

It was subsequently found that the principles of pulsed x-ray generation also have definite advantages in such traditional fields of x-ray application as flaw detection and medical x-ray diagnostics. The determining factor in these applications is not the duration of the x-ray flash, but the considerable decrease in the dimensions and weight of the radiation generator connected with the short action of the high voltage. The electrical strength of dielectrics, including vacuum, increases considerably if the time of action of the voltage becomes less than 10^{-6} sec. Discharge phenomena in solid and liquid dielectric and in vacuum which usually develop after a time exceeding the duration of the voltage pulse are excluded or occur at higher gradients. The linear dimensions of the main components of the apparatus, including the x-ray tube, decrease severalfold. Pulsed devices have, therefore, in the past decade began to be used as small-size portable x-ray sources.

Table I presents the characteristics of several portable pulsed devices developed for such problems in the U.S., U.S.S.R., and England. The source of high voltage in the Fexitron 846-2 is a Marx capacitor surge circuit. This device can operate at a repetition rate of 20 pulses per second. An x ray of steel 8 mm thick with an anode to x-ray film distance of 50 cm can be obtained after 33 pulses (total exposure time 1.7 sec); the maximum thickness of steel that can be x-rayed is 14 mm.[23] The pulsed x-ray apparatus IRA[29-32] developed in the U.S.S.R. has similar characteristics. Its special feature is the use of a pulsed transformer for obtaining the high voltage. A two-electrode x-ray tube with a needle-shaped anode has a dielectric washer near the cathode.[33] Discharge phenomena on the surface of the dielectric stabilize the conditions of the appearance of the x-ray flash. The latest model of the IRA-2D apparatus is shown in Fig. 1. It can operate at a repetition rate of 5 pulses per second. An x-ray of 20 mm thick steel at an anode-to-x-ray film distance of 100 cm requires 50 flashes (total exposure time 10 sec). The principle of pulsed transformation of the high voltage is also employed in the portable apparatus of the English firm "Hivotronic."[34] The device x-rays 50 mm thick aluminum. In addition to the AC grid, dry cells and automobile storage batteries are used as supply sources of portable pulsed x-ray units. This makes it possible to use them for testing of the quality of welds in pipelines and girders under field conditions in the absence of an AC grid. Komyak and Peliks[32] note that the IRA apparatus, first developed for the study of rapidly proceeding phenomena, has been applied mainly as a portable device for x-ray flaw detection of inaccessible components.

The next step in the problem of decreasing the dimensions and weight of x-ray units was a change to

Table I. Characteristics of some portable pulse x-ray devices

Country	Name of instrument, firm	Voltage, kV	Current, A	Duration of x-ray flash, nsec	Diameter of focal spot, mm	No. of permissible tube operations	Weight, kg	Literature
U.S.A.	Fexitron model 846-2, Field Emission Corp.	100—150	—	60	1.8	10^4	25	23
U.S.S.R.	IRA-2D, "Burevestnik" plant	300	100—200	100—200	2	$2 \cdot 10^4$	25	29, 30, 32
England	X-ray generator of the firm Hivotronic	150	1000	50	—	—	11.3	34
U.S.S.R.	RING	150	700	8	3	$2 \cdot 10^5$	1.4	35

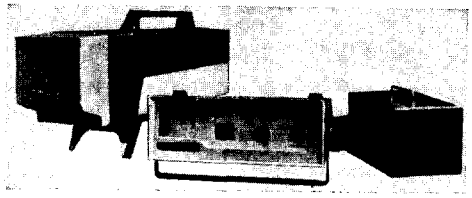

FIG. 1. Pulsed x-ray apparatus IRA-2D. Produced by the Leningrad x-ray plant "Burevestnik." Weight 25 kg; x-ray tube voltage 300 kV.

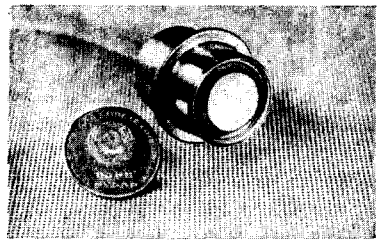

FIG. 2. Miniature pulsed x-ray tube for a voltage of 150 kV.

FIG. 3. Portable x-ray pulsed nanosecond generator RING. Operating voltage 150 kV; weight 1.4 kg.

nanosecond voltage pulses. Denholm[35] showed that for pulses with a forward-front steepness of 10^{14} V/sec and above the insulator of a 2.3-MV x-ray tube can operate at an average electric field intensity of about 80 kV/cm. With such a high dielectric strength the length of the insulator and the total dimensions of the x-ray tube decrease appreciably. The same rule is observed at lower voltages. Figure 2 shows a miniature pulsed 150-kV x-ray tube, whose volume does not exceed 20 cm^3, developed by Belkin, Avilov, and Aleksandrovich and others.[36,37] In spite of its small size, the tube can withstand more than 10^5 operations and provides well reproducible nanosecond x-ray flashes. The production of the tubes requires neither ultrahigh vacuum nor special point field emitters. In their mechanism of operation (field emission, initial stage of vacuum breakdown) such x-ray tubes are similar to Fexitrons. The duration of the voltage pulse is such that the discharge phenomena are interrupted during the phase of directed motion of the electrons from the cathode to the anode. As in Fexitrons, the duration of the high-voltage pulse is insufficient for the development of electric breakdown (a vacuum arc).

Figure 3 shows the x-ray pulsed nanosecond generator RING, developed by N. V. Belkin, É. A. Avilov, and V. I. Kolesov, which employs the tube of Fig. 2. Its dimensions are close to those of a present-day transistor receiver (140 × 100 × 60 mm). It is to be expected that during the next years portable radiation sources

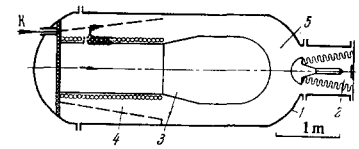

FIG. 4. Schematic cross-section of a pulsed source of hard x-ray bremsstrahlung of the type RIUS-5. K—lead for connecting the capacitor bank serving the primary winding of a pulsed "Tesla" transformer.

weighing 1—3 kg, employing components of the pulsed x-ray microtechnology, will become common not only in physical investigations, but also in numerous technical and medical applications.

2. GENERATORS OF HIGH-POWER X-RAY BREMSSTRAHLUNG PULSES

The advantages of short high-voltage pulses are used extensively in producing very powerful generators of hard bremsstrahlung. In recent years such devices have gained considerable significance in the study of the properties of materials under intense irradiation, as well as for obtaining powerful pulses of relativistic electrons.

The increase in the intensity of the x-ray flash is achieved in two ways: by increasing the energy of the electrons and by increasing the current. In the E = 2—6 MeV energy region the dose of a single x-ray flash in the direction of motion of the electrons increases as $E^{3.4}$. The large value of the exponent is connected with an increase of the coefficient of the transformation of the electron energy into x-ray quanta, as well as with a decrease in the divergence of the x-ray beam at large accelerating voltages. In order to increase the amplitude of the electron current, there is a tendency to a limiting curtailment of the internal resistance of the voltage source. This is achieved by the use of coaxial lines and by decreasing the induction of the discharge circuit by decreasing the dimensions of the high-voltage part of the device and of the accelerating tube by using highly stable dielectrics.

The phenomenon of field emission at the initial phase of the vacuum breakdown is also utilized in accelerating tubes of powerful generators of x-ray flashes. The enormous energies produced at the anode lead to considerable heating of it and to an increase in the pressure of the residual gases in the accelerating tube after each discharge.[38] Therefore such devices are, as a rule, demountable continuously pumped systems operating at a pressure of 10^{-6} torr and above. This excludes the use of field-emission pointed cathodes of the "Field Emission Corporation" type which operate only under ultrahigh vacuum conditions. For accelerating voltages of 3—10 MV and inter-electrode separations of only a few centimeters the electric fields required for the appearance of powerful field emission are provided by cathodes with radii of curvature of the order of tenths of a millimeter. It is also possible to make use of field-emission cathodes with larger radii of curvature by having numerous micropoints on the cathode surface.

In high-power generators the sources of high voltage can be Marx type capacitor surge circuits, pulsed transformers, and electrostatic generators. A small section

Table II. Characteristics of certain powerful generators of hard x-ray bremsstrahlung pulses

Country	Author and type of installation	High-voltage source	Stored energy, kJ	Voltage, MV*	Tube current, kA	Pulse dose at a distance of 100 cm, r	Pulse duration, nsec	Date	Literature
U.S.A.	Denholm, type FX-25	Resonance "Tesla" transformer	1.7	3.5/2.3	19	2	20	1965	40
U.S.S.R.	Zelenskiĭ et al	Capacitor Marx circuit	200	5/4	50	250**	500	1967	41
U.S.S.R.	Abramyan et al., type RIUS-5	Martin et al., "Hermes-2"	5.4	7/4	15	10	40	1969	38
U.S.A.	Pecherskiĭ et al.	Capacitor Marx circuit	1000	24/13	200	6800	70	1969	42, 43
CCCP	Electrostatic generator	Capacitor Marx circuit with H_2O accumulator	30	3/1.5	100	10	60	1970	47

*The numerator of the fraction indicates the voltage on the conductor or the generator voltage for no-load operation, the denominator is the voltage on the electrodes of the accelerating tube.

**A dose of 50 r is indicated in [41]; after choosing a rationalized electrode geometry in the accelerating tube the dose was increased to 250 r per pulse.

of a coaxial line or a capacitor charged by such sources, discharge to an accelerating tube through a discharger which increases the steepness of the forward front of the high-voltage pulse to 10^{14}—10^{15} V/sec. An example of such an installation is the RIUS-5 resonance pulsed accelerator proposed and constructed in 1969 by Abramyan, Vasserman, Pecherskiĭ, et al.[39] A pulsed accelerating tube 2 and a metallic cylinder 3 are placed in a cylindrical steel tank 1 (Fig. 4) filled with compressed gas. The metallic cylinder is charged up to a voltage of 7 MV with respect to the generator body by means of a "Tesla" resonance pulsed transformer 4. Such transformers have recently been used in high-current industrial electron accelerators and in x-ray installations.[40] The amplitude of the voltage pulse and the steepness of its forward front are determined by the discharge gap 5. During the breakdown of this gap the capacitance formed by the cylinder and the generator body is discharged to the pulsed tube.

In Table 2 we present the main characteristics of several high-power generators of hard x-ray bremsstrahlung radiation pulses developed between 1965 and 1970. The series FX installations proposed by Denholm[35] differ from the RIUS-5 generator which has been considered in the method of charging the conductor (electrostatic generator). Zelenskiĭ, Zavada, and their co-authors[41] built a generator in which to decrease the inductances of the discharging circuit two synchronously connected pulsed capacitor Marx circuits are simultaneously discharged onto the pulsed x-ray tube. The relatively long duration of the x-ray flash (500 nsec) is connected with the absence in the circuit of a peaking spark gap; the steepness of the voltage pulse front amounts to $\sim 2 \times 10^{13}$ V/sec.

The most powerful among the generators of hard x-ray pulses is at present, apparently "Hermes-2" developed by Martin, Johnson, and Prestwich[42,43] in the U.S. (the firm "Sandia"). A Marx capacitor pulsed circuit, a Blumlein line doubling its voltage, and a pulsed accelerating tube are placed in a common tank 6.8 m in diameter and 25 m long and filled with transformer oil. Ninety three hermetically sealed pressurized-gas spark gaps are used to switch the capacitors from a parallel to a series connection. Under similar conditions the dose at a distance of 100 cm from the target reaches 10^{11} r/sec.

The dimensions of the high-voltage pulse generator and its internal resistance can be decreased appreciably if one uses for insulation materials with a high dielectric constant ϵ. Scherrer[44] constructed capacitors with a dielectric of pure water ($\epsilon = 80$) operating at a pulsed voltage of 500 kV for experiments with exploding wires. Kulikov and co-authors[45] proposed the use of an analogous technique for obtaining large pulsed currents and strong electromagnetic fields. Mesyats and Vorob'ev noted the good commutational properties of water and of some other liquid dielectrics. Using these principles, Pecherskiĭ and his co-authors[47] proposed and constructed a pulsed generator of short x-ray flashes with water as the dielectric. The relatively low resistivity of water (10^6—10^7 ohm-cm) when the capacitor is charged by a short electrical pulse is not a limiting factor. Under similar conditions the dielectric strength of water approaches that of such perfect dielectrics as transformer oil (2—5) $\times 10^5$ V/cm. In a capacitance with water as the dielectric having relatively small dimensions (body diameter 100 cm, length 50 cm), it has turned out to be possible to concentrate an energy of 30 kJ with a voltage of 3 MV, and to realize it rapidly in a pulsed accelerating tube. On decreasing the charging time of a water capacitor down to 10^{-7} sec the specific energy concentration can reach 1 kJ/decimeter^3.

In 1967 Rex Pay[48] reported that the firm "Physics International" started planning a flash generator of hard bremsstrahlung providing at a distance of 1 m from the target a dose of about 50,000 r per 100 nsec pulse. In

order to obtain such a high radiation intensity, exceeding by almost an order of magnitude the intensity of the Hermes-2 generator, the authors intend to increase the amplitude of the electron current in the tube up to 3 MA for an electron energy of 10 MeV. We have no information about the completion of the construction of this unique installation and about the actual characteristics obtained in testing it. There is no doubt, however, that the realization of projects of such ultrapowerful sources of hard x-ray pulses is at present not connected with any difficulties of a physical nature in principle. The use of high-strength dielectrics with large values of ϵ and of contemporary techniques of generating high-voltage pulses make it entirely realistic to produce giant generators operating at pulsed currents of millions of amperes and accelerating voltages of tens of magavolts.

It should be noted that the majority of flash generators of hard x-ray bremsstrahlung considered in this section are also simultaneously used for obtaining and investigating high-power pulses of fast electrons. To this end the target (anode) in the accelerating tube is replaced by an exit window of beryllium or titanium foil. In such a way it proved possible to bring out into the atmosphere or into a chamber with rarified gas electron beams with currents of the order of tens and hundreds of kiloamperes. Graybill[49] investigated the focusing of such electron beams by the intrinsic magnetic field, as well as the conditions of ion focusing in chambers with gas pressures of 10^{-1}—10^{-3} torr. Such very powerful pulses of fast electrons are of independent interest for the problems of controllable thermonuclear fusion[50], pumping of optical quantum generators, radiation chemistry, and radiobiology.[48]

3. GENERATION OF X RAYS IN PULSED DISCHARGES IN AIR AND OTHER GASES

A vacuum or the presence of a low-pressure gas in the volume of the device were until recently considered an essential condition for obtaining x rays. All x-ray tubes operated on the left-hand branch of the Paschen curve. However, it is in principle also possible to excite x rays on the right-hand branch of the Paschen curve at gas pressures close to atmospheric. If the high-voltage pulse has a sufficiently steep front, then the discharge phenomena in the gas develop at higher voltages. The field intensity at the cathode becomes sufficient for field emission. The ionization of the gas and the emission of electrons from the cathode resulting from its bombardment with positive ions leads to a rapid increase of the number of free electrons in the gap. Under certain conditions the energy losses of the electrons in collisions turns out to be lower than the energy obtained by them as a result of acceleration in the field. X radiation should appear as a result of the braking of fast electrons in the gas and in the anode materials.

Soft x rays were first recorded in an electrical discharge in helium by Frankel et al.[51] and in air by Stankevich and Kalinin.[52] The intensity of the x-ray flashes in these experiments was low. In[52] it amounted to 6×10^4 quanta in the complete solid angle; about one hundred such flashes are required for appreciable blackening of an x-ray film. Noggle et al.[53] observed x rays with quantum energies of 11—13 keV in discharges in helium ($p \approx 760$ Torr). The radiation intensity amounted to $(2—4) \times 10^7$ photons per discharge.

Tarasova and Khudyakova[54,55,36] showed that by increasing the steepness of the voltage pulse and by decreasing the internal resistance of the source, as well as by a choice of the construction of the electrodes of an open-air spark gap, one can increase the intensity of the radiation appreciably. The amplitude of the high-voltage pulse amounted to 120—130 kV and the steepness of its forward front was about 10^{14} V/sec.

The characteristics of the x-rays depend on the discharge regime. At voltages below the breakdown voltage the x rays are produced mainly in the layer of gas in the cathode portion of the gap. With such a regime one observes a diffuse glow near the cathode. In discharges with clearly expressed channels (breakdowns) part of the fast electrons may bombard the target. In this case the emission of x rays occurs simultaneously from the anode and from the gas layer. The duration of an x-ray flash does not exceed several nanoseconds.

A high-temperature plasma in hydrogen, helium, xenon, and other gases in high-current electric discharges can also be a source of short flashes of x rays. In such experiments one usually makes use of capacitor banks with current rise rates $dI/dt \approx 10^{10}$—10^{12} A/sec; the amplitude of the current pulse is within the range of 10^5—10^6 A. The first investigations of such radiation by Lukiyanov and Podgornyĭ[56] and by Artsimovich et al.[57] were carried out in cylindrical chambers with insulating walls where under the action of the magnetic field of the current the discharge contracted into a narrow pinch along the axis of the chamber (straight cylindrical pinch). Subsequently, T. I. and N. V. Fillipov and Vinogradov,[58] Mather and Bottoms,[59] and others observed that the intensity of the radiation increases appreciably with discharges in chambers with metallic walls (non-cylindrical z pinch).

Under such conditions there are two sources of x-ray flashes with different spectral characteristics separated in the chamber volume. Soft x rays with energies of 1—10 keV appear at the focus of convergence of the plasma cloud. According to the data of Beckner[60] such a plasma focus provides a dose of about 60 r at a distance of 10 cm per 200—300 nsec pulse. The soft x rays of the plasma focus represent the bremsstrahlung, recombination and line emission of the dense, high-temperature plasma.

The anode of the chamber and the layer of metallic vapors near it due to the contact between the pinch and the anode are the source of harder x rays. According to the data of Agafonov et al.[61] at the instant of cumulation of the noncylindrical z pinch fields are induced which accelerate electrons to energies of 100—300 keV. The electron current entrained into such an acceleration process amounts to 10—100 percent of the total discharge current. The dose of hard x rays lies within the limits of 0.1—1 r at a distance of 100 cm from the target per 100-nsec pulse. So far there is no complete theory of the origin of the hard x rays which is in quantitative agreement with the experimental data. It is proposed that local radial deformations of the pinch can give rise to a rapid rise of the magnetic field and produce conditions for linear or cyclic acceleration of electrons in induced electric fields.

Table III. Some radioactive isotopes emitting characteristic x rays and low-energy gamma rays

Element	Isotope	Type of decay	Half-life, years	Quantum energy, keV		Radiation intensity	
				x rays	gamma rays	quanta/g-sec	quanta/cm²-sec
Vanadium	$_{23}V^{49}$	ε-capture	0.915	K-sereis Ti 4.5; 4.9	—	$5.9 \cdot 10^{13}$	$1.6 \cdot 10^{11}$
Iron	$_{26}Fe^{55}$	ε-capture	2.6	K-sereis Mn 5.9; 6.5	—	$2.5 \cdot 10^{13}$	$1 \cdot 10^{11}$
Plutonium	$_{94}Pu^{238}$	α-decay	84.6	L-series U 13.6; 17.2; 20.2	—	$8.6 \cdot 10^{10}$	$3.8 \cdot 10^{8}$
				—	43.5	$2.5 \cdot 10^{8}$	$4.7 \cdot 10^{6}$
				—	99.8	$5.3 \cdot 10^{7}$	$1.1 \cdot 10^{7}$
Americium	$_{95}Am^{241}$	α-decay	458.1	L-series Np 13.9; 17.7; 20.8	—	$2.8 \cdot 10^{10}$	$1.9 \cdot 10^{8}$
				—	26.4	$3 \cdot 10^{9}$	$1.3 \cdot 10^{7}$
				—	33.2	$1.3 \cdot 10^{8}$	$1.1 \cdot 10^{6}$
				—	43.4	$8.4 \cdot 10^{7}$	$1.6 \cdot 10^{6}$
				—	59.6	$4.3 \cdot 10^{10}$	$2 \cdot 10^{9}$
				—	99	$2.8 \cdot 10^{7}$	$5.5 \cdot 10^{6}$
				—	102.8	$2.3 \cdot 10^{7}$	$5.2 \cdot 10^{6}$

4. RADIOACTIVE SOURCES OF X RAYS AND LOW-ENERGY GAMMA RAYS

The progress in the techniques and technology of production of artificial radioactive elements has rendered isotopes whose x-ray and gamma radiation corresponds closely to the spectral characteristics of x-ray tubes available in practice. Radioactive sources offer the advantages of highly constant intensity and energy, the possibility of obtaining radiation without employing an electric supply, and high reliability. Along with the widely known sources of hard gamma rays based on the radioactive isotopes Co^{60} and Cs^{137}, in the past decade numerous methods and devices have been developed and have attained independent significance; these employ various radioactive isotopes as sources of x radiation with energies up to 100 keV.

Table III lists data on several radioactive isotopes that emit characteristic x rays and low-energy gamma rays (up to 100 keV). The isotopes V^{49} and Fe^{55} decay by means of the ε-capture scheme. They are convenient sources of soft, practically "pure" characteristic x radiation of titanium and manganese. The transuranium isotopes Pu^{238} and Am^{241} undergo α decay. In the past they were mainly used as α emitters. In recent years these isotopes have come to be used as sources of x rays and low-energy gamma rays.

The last two columns of Table III present data on the quantity of x-ray and gamma quanta emitted per second per gram of pure isotope, as well as that emitted from one square centimeter of surface into a solid angle 2π. The radiation yield from a unit of surface (the last column) is particularly important for practical purposes. This yield was calculated for a layer of isotope whose thickness corresponded to the range of the radiation of the given energy. By virtue of the relatively low energy of the quanta the self-absorption of the radiation in the source material is considerable and the range of the characteristic x radiation or of the low-energy gamma rays is relatively small. It amounts to 15 microns for the characteristic x rays of the Fe^{55} isotope and about 80 microns for the 59.6-keV gamma rays of the Am^{241} isotope.

The intensity of the radiation of radioactive isotopes is considerably lower than that of conventional x-ray units. The yield of characteristic x rays of manganese from the surface of a source of the isotope Fe^{55} (10^{11} quanta/cm² sec) is approximately equal to that of an x-ray tube with a manganese anode operating at a voltage of 15 kV and a current of 50 μA. Such tubes are commonly used with currents of 5—15 mA. The intensity of the emission of a tube exceeds in this instance by more than two orders of magnitude the x-ray intensity emitted by the Fe^{55} isotope. For the isotopes Pu^{238} and Am^{241} this difference in the intensities is more appreciable. Nevertheless, the possibility of an appreciable decrease in the distance between the radioactive source and the irradiated object, the use of high-speed methods and other processes, makes it possible in many instances for radioactive isotopes to compete successfully with the traditional techniques of obtaining x rays.

The isotopes in Table III represent a rather large range of quantum energies—from 4.5 to 60 keV. Fluorescent targets irradiated by these isotopes can constitute radiation sources of intermediate energies. The excitation of fluorescent radiation is particularly efficient if the atomic number Z of the target element is 1—6 units below the Z of the element emitting the characteristic x rays. For such a relationship between the energies of the primary and secondary radiation, the intensity of the fluorescent radiation may reach tens of percent of the primary-beam intensity.[62]

Figure 5 shows two arrangements of the radioactive source and of the fluorescent target. When the dimensions of the emitter are immaterial, one uses the arrangement in Fig. 5a. The radioactive source 1 is in the shape of a small disk located near the center of a hemispherical fluorescent target 2. This method is marked by very high efficiency, since the primary radiation of the source is utilized within a solid angle of almost 2π. The arrangement 5b is less efficient but makes it possible to obtain sources of fluorescent radiation of small dimensions. The radioactive source is in the form of a ring with the fluorescent target located opposite its active layer. The opening in the ring determines the active dimension of the radiation source.

We shall describe several methods and devices in whose practical realization the advantages of radioactive

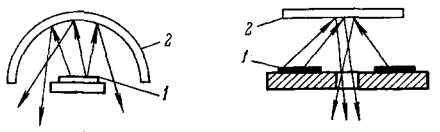

FIG. 5. Diagrams of the arrangement of the radioactive source (1) and of the fluorescent target (2) for exciting secondary characteristic x-rays. a) Hemispherical target; b) source of limited dimensions.

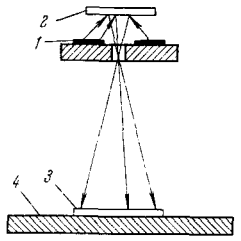

FIG. 6. Diagram of a radioactive contact x-ray microscope. 1—radioactive source, 2—fluorescent target, 3—investigated object-, 4—fine-grain photographic plate.

sources of x rays turned out to be particularly important. In recent years, in connection with the development of reactor technology for the production of the iron isotope Fe^{55} [63] it has become possible to obtain relatively low-cost sources of this isotope. A series of devices in which radioactive iron constituted the source of soft characteristic x rays has appeared.

The radioactive contact x-ray microscope with a Fe^{55} isotope makes it possible to investigate small entomological and botanical objects and thin hystological sections and to determine the chemical identity of the revealed structure. 1 and 2 are the radioactive source and the fluorescent target whose radiation irradiates the investigated sample 3 which is in close contact with a fine-grain photographic plate 4 (Fig. 6). If the opening in the source is small (0.3—0.5 cm) and the observed object is no more than 0.1 mm thick, then for distances of 5—10 cm between the source and the photographic plate the smearing of the image due to geometric factors does not exceed several microns. The contact x-ray photograph obtained in such a manner can be magnified after development by a factor of 10—60.

Figures 7 and 8 are prints of contact x-ray micrographs of hystological sections of a heart valve and lung of persons who died of an infract and of silicosis.[64] The section of the heart valve was x-rayed with direct radiation of a source with the Fe^{55} isotope (λK_α = 2.103 Å). Fluorescent radiation of a sulfur target (λK_α = 5.36 Å) was used to reveal the distribution of the silicon compounds in the section of lung tissue (Fig. 8). The sulfur radiation is preferentially absorbed by silicon and the dark sections surrounding the bronchus reveal clearly the regions occupied by compounds of this element. The control x-ray photograph of the same section was made by using silicon characteristic radiation (λK_α = 7.11 Å). The mass absorption coefficient for this radiation in silicon is several times smaller than the absorption coefficient for sulfur radiation. A comparison of the x-ray micrographs obtained with radiation preferentially absorbed by a given element with those obtained with radiation of a target of this element which is weakly absorbed by it makes it possible to establish the chemical identity of the structures determined by means of the x-ray microscope.

FIG. 7. X-ray microphotograph of a histological section of a heart valve of a person who died of an infract. The dark inclusions are regions of concentration of calcium and sodium salts. Optical magnification X 10.

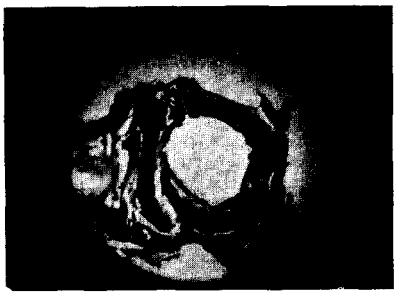

FIG. 8. X-ray micrograph of a histological section of the lung of a person who died of silicosis. The dark inclusions around the bronchus are concentrations of silicon compounds. Optical magnification X 10.

The use of the characteristic x rays emitted by the isotope Fe^{55} in x-ray structure investigations of polycrystalline samples and single crystals is interesting and promising. The first proposals and experiments in this field were published in this country in 1965.[65] Analogous investigations were published in the U.S. by Preuss, Toothacker, and Bugenis[66] in 1966. The low radiation intensity of the radioactive isotopes compared with x-ray diffraction tubes led in the first experiments on the photographic recording of reflections to very long exposure times (exceeding 100 hours). The use of axial focusing of a widely divergent x-ray primary beam due to Preston and Al'tshuler[67] made it possible to remove this shortcoming to some extent. In the "Rada" camera, utilizing such focusing, a 1 × 3 mm strip of radioactive iron foil is mounted in place of the entrance slift.[68,69] With a total activity of the source of about 60 μCi (6—8 percent enrichment in the Fe^{55} isotope) x-ray patterns of polycrystalline samples of the primitive cubic system (copper, nickel) are obtained after 1—3 hours.[70] Toothacker, Bugenis and others have published a number of papers in which the source with the Fe^{55} isotope was used in Debye-Scherrer cameras.[71-73]

Compared with the generally accepted method of x-ray diffraction investigations the advantages of cameras with radioactive sources of characteristic x rays are the complete independence of these devices (the absence of a source of electrical energy), their small dimensions and weight, and the high stability of the radiation intensity. Such a technique is of definite interest for the x-ray diffraction analysis of geological samples in prospecting for minerals under field conditions. Sources with the Fe^{55} isotope can find application in special devices for the study of the structure of mater-

ials at high and low temperatures, in measurements of internal stresses in parts of machines and metal structures and in other similar problems.

The soft x rays of radioactive sources were used by Cook, Mellish and Pein[74] to measure the thicknesses of thin coatings. The method of determining the thickness of metallic foils and organic films by the absorption of the characteristic or bremsstrahlung x radiation excited by the β particles of tritium (E_{max} = 18 keV) is described in[75]. The measurement of the thickness of coatings with aid of sources with the Fe^{55} isotope is based on the excitation of the fluorescent radiation of the substrate material or of the coating. The thickness of the coating is determined from the absorption of the substrate radiation by the coating or from an intensity measurement of the radiation of the coating. A sensitivity of 6×10^{-6} g/cm^2 was attained for certain substrate-coating pairs (for instance, gold coating on lead).[76]

The number of possible substrate-coating combinations can be extended considerably by the use of diffraction. This method consists of the spatial separation and recording of diffraction peaks at different Bragg angles from the coating and from the substrate. Within certain limits the increase in the intensity of the diffraction line of the coating is proportional to the increase in its thickness. The intensity decrease of the diffraction line of the substrate due to its attenuation in the material of the coating is also uniquely related to the thickness of the latter. Making use of the characteristic radiation of the Fe^{55} isotope and of the (113) diffraction line of gold, it turned out possible to measure a gold layer 1000-Å thick on a copper substrate with an error not exceeding 10 percent.

Radioactive isotopes which emit soft x rays and low-energy gamma rays have turned out to be convenient sources in x-ray spectroscopic investigations. The isotope Fe^{55} is used to excite the fluorescent radiation of light elements from aluminum to chromium (Z = 13–24) in quantitative analysis employing spectrographs without crystals.[77] In such devices the characteristic radiation of the elements of the test sample is recorded separately as a function of the energy of the x-ray quanta. X rays and gamma rays of Pu^{238} and Am^{241} are used in the analysis of elements of the central portion of the periodic table (Z = 24–69).[78] These compact sources of radiation make it possible to construct small portable units for the analysis of samples under the conditions of geological prospecting in determining the concentration of mineral raw material in adits, and in other similar problems.

The properties of the radioactive isotopes under consideration may turn out to be useful in some radiobiological and medical applications. Notwithstanding the low radiation intensity compared with x-ray units, on close contact with the irradiated surface these sources are capable of maintaining a sufficient radiation dose for observation of radiobiological effects. Applicators of the isotope Fe^{55} with a 6–8 percent enrichment provide under such conditions a dose of 6000–8000 r/hour. The required therapeutic effect can be obtained on applying such an applicator to the irradiated part for several minutes. In its characteristics the radiation of the Fe^{55} isotope corresponds roughly to the bremsstrahlung of an x-ray tube operated at 12–15 kV, and the radiation of Am^{241} corresponds to a therapeutic x-ray unit with a voltage of 120–150 kV. An advantage of radioactive isotopes is the possibility of radiation therapy of internal cavities into which it is difficult, and sometimes impossible, to introduce a therapeutic x-ray tube. In radiobiological experiments the soft x rays of the Fe^{55} isotope make it possible to localize the irradiated layer because the range of this radiation in the biological object is small (0.5–1 mm). An important practical advantage of radioactive sources of x rays and low-energy gamma rays is the simplicity of shielding the servicing personnel from the radiation. When materials are used that attenuate preferentially the radiation of the isotope, the weight and dimensions of the containers and installations decreases considerably. Sources of the Fe^{55} isotope with an activity of some tens of curies can be safely stored and transported in containers weighing about 0.1 kg. Containers for Pu^{238} and Am^{241} isotope sources are also of relatively small dimensions and weight. This makes it possible to utilize the sources and devices considered above in ordinary rooms without cumbersome shielding arrangements used in working with sources of hard gamma rays based on Co^{60} and Cs^{137} isotopes.

The flash technique, field emission, discharges in gases and radioactive isotopes do not, of course, exhaust the physical phenomena and principles which are used in producing new sources of x rays. There is an interesting and promising report on pulsed iron-free betatrons with circulating currents of ~ 90 A with an electron energy of 100 MeV.[79] The duration of a bremsstrahlung flash in such installations can vary between several tens of nanoseconds up to tens of microseconds. There are also other trends. Nevertheless for problems whose solution requires the use of miniature, portable x-ray units the flash technique and tubes with field-emission cathodes have advantages over other methods of generation of radiation. The use of radioactive isotopes is promising whenever one requires, along with minimal dimensions of the source, high stability and a small expenditure of electrical energy. One should also expect new developments in the use of pulsed generation of very powerful flashes of x-ray bremsstrahlung and relativistic electrons in devices with direct acceleration with megavolt voltages and megaampere electron currents.

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