Information from the Book "X-Ray Apparatus"

Rentgenovskiye Apparaty, V. K. Shmelev,
Moscow/Leningrad 1949

INFORMATION FROM THE BOOK 'X-RAY APPARATUS'

V. K. Shmelev

(Note: The following material consists of four portions extracted from the book Rentgenovskiye Apparaty, written by V. K. Shmelev and published 1949 in Moscow/Leningrad by the State Power Press. Namely, the following four:

(1) The Russian editor's comment, page 2 (of the original);

(2) The author's preface; pages 3 and 4;

(3) Table of Contents, pages 5, 6, 7; and finally,

(4) The last chapter, the 7th, entitled High-Voltage Apparatus, pages 279 to 300, with list of sources used in compiling this last chapter.)

(1) The Russian Editor's Comment:

This book represents a monograph devoted to the electrical side of x-ray apparatuses. The first two chapters give certain elementary information on x-rays and x-ray tubes. The computational material expounded in the book concerns rectifier circuits that are employed in the construction of x-ray apparatus. The book is intended for engineering and technical workers who have to do with the production and maintenance of x-ray apparatus and its installation on the spot. The book can also serve as a text for students in electrical-engineering and power-engineering colleges offering courses on "roentgenotechnics", and also for students at electrical technical schools offering courses on "roentgen apparatus".

(2) Author's Preface:

The x-ray apparatus assumes an isolated position in electrical engineering, as demonstrated by its specificity. This has led to the situation that in the electrical engineering literature small attention is paid to x-ray apparatus. In general textbooks on x-ray engineering and practical applications of x-rays, x-ray apparatuses are described only among other things. At the same time, the need for a systematized work devoted to the electrical side of x-ray apparatuses is very great. Such a work is required mainly by engineering-technical workers having business with the production and repair of x-ray apparatus and its installation on the spot. The present book is intended to fill this gap.

In compiling this book, the author used his own personal experiences gained in the field of x-ray apparatus construction, besides the usual literature. The calculations carried out in the book concern rectifier circuit of x-ray apparatuses. The author did not set as his goal to give all the computational material need for designing and constructing an x-ray apparatus. The descriptive part contains the most typical examples of existing x-ray apparatuses mainly Russian. The number of described models is held to a minimum: the development of x-ray apparatus construction goes at a rapid pace, and to allot too much space to a description of actual designs would be inexpedient. At the same time, by comprehending sufficiently the theoretical foundations and having certain practical experiences, one can without special difficulty, acquire x-ray technology from analyzing any model.

The first two chapters of the book are devoted to x-rays and x-ray tubes. The material of these chapters does not pretend to completeness, and contains only the information necessary for understanding the operation of x-ray apparatuses. In the list of literature given are placed only those sources which were used in the compilation of this book.

The author expresses his acknowledgements to professor V. V. Yasinskiy, who reviewed the book; and also to engineer V. A. Vitka, candidate-of-technical-sciences V. V. Dmokhokskiy, and engineer G. K. Yevdokimov, who read the book in manuscript and gave valuable comments. All corrections of mistakes in this book are to be

sent to the following address: Moscow, Shlyuzovaya naberezhnaya [quay], d. 10. Gosenergoizdat [State Power Press].

(3) Table of Contents:

	Page
Introduction	8
Chapter I. Certain Information on X-rays	
1. Generation of x-rays and their main properties	13
2. Dependence of x-rays on anode voltage and anode current of x-tube	20
3. Quantitative and qualitative evaluation of x-rays	26
4. Application of x-rays in medicine and engineering	27
a) x-ray diagnosis	
b) x-ray therapy	
c) x-raying of materials	
d) x-ray spectral analysis	
Chapter II. X-Ray Tubes and High-Voltage Tubes	
5. X-ray tubes	37
6. Various types of x-ray tubes and their properties:	41
a) diagnostic tubes	
b) therapeutic tubes	
c) tubes for x-raying materials	
d) tubes for structural analysis	
7. Characteristics of x-ray tubes	53
8. Passage of current through x-ray tube with poor vacuum	59
9. High-voltage kenotron	60
10. High-voltage gasotron	63

Page

Chapter III. High-Voltage Part of X-Ray Apparatus

11. Main transformers 66
12. Active resistances, inductances of leakage, and internal capacitance of the main transformer 73
13. Power of the main transformer 76
14. Main transformers with variable coefficients of transformation 77
15. Filament transformers 79
16. High-voltage condensers 81
17. Generator installation 83
18. Electrical strength of the generator 88
19. Open high-voltage wiring 89
20. Problems of electrical safety 90
21. High-voltage x-ray cable 92
22. Protective casings for x-ray tubes 95
23. Block transformers 100
24. Pumps for cooling the anodes of x-ray tubes 103
25. Measuring the anode current of the x-ray tube 104
26. Measurement of high voltage 105

Chapter IV. Rectifier Circuits of X-Ray Apparatus

27. General discussion 113
28. Half-wave tubeless circuit 116
29. Computing the currents and tube power in a half-wave tubeless apparatus 119
30. Voltage drop in half-wave tubeless apparatus 125

		Page
31.	Influence of cable capacitance on operation of half-wave tubeless apparatus	130
32.	Half-wave circuit with tubes in the primary circuit	132
33.	Half-wave circuit with tubes in the secondary circuit	136
34.	Influence of cable capacitance on operation of half-wave apparatus with tubes in the secondary circuit	139
35.	Four-tube bridge rectifier circuit	144
36.	Six-tube bridge rectifier circuit	150
37.	Doubling circuit with pulsating voltage	155
38.	Calculating the currents, tube power, and voltage drop in apparatuses according to the doubling circuit with pulsating voltage	159
39.	Influence of cable capacitance in apparatuses according to the doubling circuit with pulsating voltage	166
40.	Doubling circuit with constant voltage	168
41.	Tripling circuit	176
42.	Summary of the main electrical quantities for rectifier circuits	184
43.	Overvoltage in x-ray apparatus	186
44.	Impulse feeding of x-ray tube	197
Chapter V.	Low-Voltage Part of X-Ray Apparatus	
45.	Regulator auto-transformers with insoldering	203
46.	Regulation of the voltage by means of commutators	206
47.	Variators	210
48.	Regulation of the filament in x-ray tube and high-voltage tubes	214

Pages

49. Voltage drop in x-ray apparatus and feed net 215

50. Correction of the net voltage. Compensation of voltage drop. Stabilization of voltage. 217

51. Starting and switching of x-ray apparatus 223

52. Time relay and exposure relay 228

53. Protection during short circuits and overloads 237

54. Signaling and blocking 238

55. Control panels 239

Chapter VI. Typical Designs of X-Ray Apparatus

56. Diagnostic apparatus 241

57. Portable diagnostic apparatus 243

58. Movable diagnostic apparatus 246

59. Light-duty stationary diagnostic apparatus 250

60. Powerful stationary diagnostic apparatus 256

61. Apparatus for fluorography 265

62. Therapeutic apparatus 266

63. Apparatus for x-raying of materials 270

64. Apparatus for structural and spectral analyzes 274

Chapter VII. Superhigh-Voltage Apparatuses /Note: This chapter is translated in full/.

65. General considerations 279

66. Apparatuses with voltage multiplication 281

67. Half-wave apparatus with resonance transformer 285

68. Impulse generators 288

	Page
69. Electrostatic generators	289
70. Betatron	290
Literature Used in the Writing of the Book	296
Alphabetical Index	300

(4) Chapter VII. Superhigh Voltage Apparatuses /Note: Figures are given in the appendix/.

65. General Considerations

In this book super-high voltages mean voltages higher than 400 kV_{max}. High-voltage apparatus is used for feeding x-ray tubes that generate very stable x-rays for therapy and for x-raying of materials. Superhigh-voltage apparatus however is used mainly for the acceleration of electrons and ions in special discharge tubes, with the object of bombarding by these particles various targets for the investigation of problems of atomic physics.

This field of study has brought about in the last 15-20 years a very rapid development of special superhigh-voltage construction. Simultaneously there have appeared installations in which electrons and ions are given tremendous energies (up to 100 million and more electron-volts) without the use of superhigh voltage.

Installations of the cyclotron and betatron type are related to them. Here are briefly described some of these apparatuses and installations, mainly for obtaining x-rays in practical applications.

Ordinary two-electrode x-ray tubes are manufactured for voltages up to 400 kV_{max}. Fundamental obstacles in the way of creating similar tubes for higher voltages are: 1) spontaneous electron emission due to the great intensity of the electric field in the electrodes and leading to a powerful discharge through the tube; and 2)

2) non-uniform distribution of voltage along the surface of the tube. For this reason, in superhigh voltages the so-called sectioned (cascaded) tubes are used, in which the electrical fields are smoothed by the use of intermedial electrodes with impressed potentials.

Protection from x-rays is a very serious question in superhigh voltages. Protection is more easily secured if the source of radiation is a focus spot, situated in the depth of a hollow grounded anode. For this reason, sectioned tubes are usually made with a hollow anode, although grounding of the anode does complicate the insulation of the entire installation. Another advantage of the hollow anode is that it practically completely recovers the reflected electrons. An unsoldered sectioned x-ray tube of 500 kV_{max}-voltage with a hollow grounded anode is shown in Figure 180. Intermedial electrodes, representing hollow cylinders, are held fast to metallic rings made of fernic alloy soldered to glass. The tube is designed to operate in oil. The length of its insulated part is about 700 mm, and its diameter is about 90 mm. The hollow anode is made from a nickel tube 600 mm long and 50 mm diameter. The mirror of the anode is made of tungsten. The anode is surrounded by a water jacket to cool it, and a massive lead hood letting in rays only through the window. The tube possesses magnetic focussing and a controlling grid surrounding a cathode of ordinary design.

In Figure 181 are shown such tubes of 1 and 2 MV tension voltages.

These tubes are designed for gaseous insulation under pressure. The 1-MV tube consists of 12 sections, the length of it without the hollow anode being 750 mm and its diameter 90 mm. The 2-MV tube consists of 24 sections, its length being approximately twice as great. The tubes do not have controlling grids.

Some sectioned electron tubes operate with a pump. There are also sectioned ion tubes. The most unusual electro-vacuum apparatus is the ring vacuum tube, which is used to accelerate electrons in the betatron (70).

66. Apparatus with Voltage Multiplication

To obtain superhigh voltages one can employ circuits that double and triple the voltages, considered earlier in Chapter IV. Thus, the domestic apparatus designed for a symmetric voltage of 500 kV_{max}, is erected according to a double circuit of voltage doubling [Literature 69]. In the apparatus high-voltage transformers and condensers for voltages of 110 kV_{max} are employed. At such voltages one must ensure that the secondary winding of the transformer is insulated from the body. This required the insulation of the transformer containers from the ground and the introduction of separate transformers into the main circuit (Figure 182).

The cathode filaments of the kenotrons and x-ray tube are fed by filament transformers; for those of them which are, with respect to the ground, under double or triple voltage, the supply is fed also through one or two separate transformers. Filament transformers and the separate transformers feeding them are placed in the general containers with the transformers of the main circuit and with the condensers Kenotrons with closing voltage of 220 kV_{max} are used in the apparatus.

Figure 183 show an apparatus constructed according to the double circuit of voltage doubling with pulsating voltage and rated for a symmetric tension of 800 kV_{max}. The generator installation comprises a high-voltage 400 kV_{max} oil transformer 1, with grounded middle point, two high-voltage oil condensers 2 and two high-voltage kenotrons. The condensers are designed for 200 kV_{max} voltage, and the kenotrons for 400 kV_{max}. For the incandescent x-ray tube and one of the kenotrons small generators are used, which are mounted in the interior of the extrodes 3 and set into motion by means of a motor, situated in the interior of a grounded electrode 4, with the aid of insulated axles 5. Another kenotron, whose cathode is at ground potential, is heated by means of filament transformer.

In installations designed for still higher voltages one has recourse to series (cascade) connection in order to simplify the insulation. These installations are generally designed for investigations in the field of atomic physics. Figure 184 represents the circuit of a 10-mA installation of 1-MV with respect to the ground having four cascades, built according to the constant-voltage doubling circuit.

The installation consists of five vertical columns. One column contains high-voltage transformers; a second contains intermedial (separate) transformers; a third and fourth column are reserved for heating high-voltage kenotrons. The kenotrons are disposed between the columns. In the interior of each of these two columns is situated a motor, which set the generators in motion. The motor is connected by means of a vertical insulating shaft with a generator of the lower cascade; the latter is connected by means of the same kind of shaft with the following generator, and so forth. High-voltage condensers make up the fifth column. The total height of the installation is 7 m.

To obtain a constant high voltage, the circuit for the multiple multiplication of voltage is also used. It is distinguished by the fact that it uses altogether only one high-voltage transformer, whose voltage is increased many fold by means of high-voltage condensers. This circuit is shown in Figure 185. Transformer T_1, condenser C_1 and tube V_1 constitute the doubling circuit with pulsating voltage charging the condenser C_2 to a voltage equal to twice the voltage amplitude of the transformer. The same voltage is charged across tube V_3 and condenser C_3. Continuing the discussion of the succeeding stages we are convinced that during idling all the other condensers obtain the same voltage. Thus the voltage of the installation equals $n \cdot U_{max}$, where n is the number of stages (number of condensers), and U_{max} is the voltage amplitude of the transformer. Here the even stages give relative to the ground a constant voltage; the odd stages however, are pulsating with a pulsation equal to the doubled voltage amplitude of the transformer. The counter voltage of the tubes is equal to this same quantity.

The absence of a complicated cascade of the main transformers simplifies the construction and permits decreasing the size of the installation in comparison with that of Figure 184. Moreover this creates a great loss of voltage during load, which rapidly increases as the number of stages increases.

Figure 186 shows the circuit of an installation of 1.25 MV with respect to the ground. The main circuit in this installation is fed by a generator of increased frequency (200 cycles/sec), which permits decreasing the capacitance of the condensers. Gasotrons (gas rectifiers) are used as tubes with closing voltage of 225 kV_{max}. The incandescent filaments of the gasotrons are supplied from a high-frequency tube generator (500 kilocycles) across small auto-transformers. Current of high frequency goes in series across condensers, auto-transformers and resonance filters, which represent for a 500 kilocycle current a small resistance and practically do not allow a constant current and current of low frequency. The filters should admit a pulsating voltage with a maximum of 225 kV_{max}. The auto-transformers are protected by resonators. The capacitances in the circuits of the tube cathodes compensate for the inductance of the auto-transformers. The load is connected to the electrode, which is connected to the installation across high-voltage buffer resistance R_d. High voltage is measured with the aid of a multi-ohm divider of resistance R_m and a electrostatic voltmeter connected in parallel with a small part of the divider directly joined to its grounded end. The total height of the installations is 5.5 meters. Such an installation was manufactured for a symmetric voltage of 3 MV /Literature 6 and 8/.

Domestic scientific-research institutes have installations of special manufacture. It is necessary to notice that cascaded installations are very suitable for feeding sectioned (cascaded) tubes. Intermedial electrodes of the tube are connected with cascades of the installation.

67. Half-wave apparatus with resonance transformer.

For feeding sectioned x-ray tubes, it also seems expedient to use a half-wave tubeless circuit. In this case the forced distribution of voltage among sections of the tubes is effected by connecting the intermedial electrodes of the tube to the unsoldered portions of the secondary winding of a high-voltage transformer. Having at one's disposal an x-ray tube in a general jacket with a high-voltage transformer, one can obtain a much more compact construction of a superhigh-voltage block-transformer.

In an apparatus of similar construction for 500 kV_{max} with grounded anode, the high-voltage transformer and sectioned x-ray tube with hollow anode (Figure 180) are immersed in oil. The anode of the tube protrudes externally and is cooled by running water. The high-voltage transformer has a magnetic circuit with air gaps, whose purpose is to compensate for the capacitance component of the primary current due (i.e. component) to the natural capacitances of the secondary winding of a high-voltage transformer.

Further work on the perfection of this construction led to the creation of the gas-insulated block-transformer with tension of 1 MV with respect to the ground. Here, high voltage is generated by a resonance transformer without a steel core, as a result of which the apparatus is much more compact. The first apparatus of this type used a sectioned x-ray tube with hollow anode, operating with a pump [Literature 70]. In the succeeding design an unsoldered tube replaced it (Figure 181). Below a short description of this apparatus is given [Literature 71].

The theoretical scheme of the apparatus is shown in Figure 187. The motor actuates a generator of triple frequency (180 cycles). The generator is connected to the primary winding of a resonance transformer across a capacitance, serving to compensate for action of the generator's leakage reactance. The secondary winding of the high-voltage transformer is composed of separate flat sections. The voltage of the transformer increases along the winding in proportion to the distance from the grounded end, situated in the immediate vicinity of the primary winding. Intermedial electrodes of a sectioned x-ray tube are connected to sections of the secondary winding of the high-voltage transformer. The filament of the cathode is heated by special windings. The heating-filament current is regulated by means of choke coil actuated by a motor connected to the choke coil by aid of a glass shaft. An x-ray tube possesses magnetic focussing of the electron beam.

The leakage inductance of the transformer's secondary winding and its capacitances generate an oscillatory circuit, by which the parameters L and C are chosen so that the contour turns out to be tuned in resonance with the external (primary) voltage. Owing to this, the oscillations in the secondary circuit acquire a great amplitude and the secondary voltage exceeds by many times the primary voltage.

The inductance of the apparatus described is equal to 15,600 H, the equivalent capacitance is 50 micromicro-F. The capacitance current in the secondary winding reaches 56 mA. Since the anode current of the tube does not exceed 3 mA, the presence of the load does not show a substantial influence on the electrical oscillations in the secondary circuit. For the same reason one can disregard the difference of the maxima of half-waves of the secondary voltage.

The secondary winding of the transformer is grounded across a measuring circuit. The filter consisting of low-voltage choke coil and condenser separates the direct and alternating components of the secondary current. The first, representing also the anode current of the x-ray tube, goes through a magnetoelectric device; and the second (which represents with a sufficient degree of exactness the alternating current of the resonance circuit) goes across an electromagnetic device. Since the alternating current of the resonance circuit is proportional to the maximum secondary voltage, it turns out to be possible to graduate the electromagnetic apparatus directly in kilovolts.

Electrical oscillations in the secondary circuit always possess a harmonic character even if the primary voltage strongly deviates from sinusoidal. Owing to the fact that the circuit is resonant, one need not fear overloading when switching the apparatus in or out.

A schematic cross-section of a block-transformer is given in Figure 188. The absence of a steel core permits putting an x-ray tube in the center of the block-transformer, on the axis of winding, which led to a very rational utilization of the volume and created a more nearly perfect screening effect of the tube. The magnetic current of the secondary winding is completed through a steel yoke, constructed to lessen the loss from individual strips of plate steel, reenforced with the steel jacket of the block-transformer over all its diameter. Freon gas (CCl_2F_2) under 4 atmospheres of pressure is the insulating medium. The electrical stability of freon is approximately three times greater than air under the same pressure. /Note: A still better gas insulation is elegas. Literature 72/. To increase heat exchange, artificial circulation of the gas is employed. The jacket of the block-transformer is 1.2 m high and 0.9 m in diameter. The weight of the block-transformer is about 700 kg.

The apparatus described can be used in deep-tissue therapy and x-raying of materials. In the latter case the block-transformer is fastened to a travelling hoisting crane and thus acquires great mobility. To photograph with its aid steel objects 200 mm thick for a focal distance of 0.9 m requires exposures of 200 mA-min.

In the past years a 1.5 mA apparatus of such a type with voltage 2 MV relative to the ground has been released [Literature 73]. The block-transformer is 2.4 meters high and 1.5 meter in diameter. The x-ray tube is shown in Figure 181. One has succeeded in shortening to 4-5 mA-min the exposure in x-raying of steel objects 200 mm thick for focal distance 0.9 meter.

68. Impulse generators

The greatest advantage of impulse feeding of an x-ray tube for superhigh voltages is the ability of insulation to sustain, under very short impulses (of the order of microseconds), a noticeably greater voltages than by ordinary feeding. Owing to this, superhigh-voltage impulse x-ray apparatuses can obtain wide-spread use in not only microsecond, but also ordinary x-raying of materials.

The 1-MV impulse generator (relative to the ground) [Literature 74] represents a finished industrial design. The generator is enclosed in a steel jacket of volume 0.73 m^3, well-filled with dehumidified transformer oil with increased electrical stability. The generator consists of 25 condensers (of 40 kV each), generating columns, arranged vertically. Insulation material is specially prepared getinax (or textolite).

The impulse generator is fed from an x-ray high-voltage transformer of 4 kVA power, situated outside the jacket. Gas dischargers are located in the interior of the jacket in oil, in insulated containers.

The ion discharge tube with grounded anode is situated in the upper part of the jacket and is distinguished by its small dimensions. It consists of insulated and metallic discs, assembled alternately. The insulated discs are made of barium borate micalex; their number equals 20. The tube is 22 cm long and 21 cm in diameter. The tube works by pump under pressure of the order of 10^{-3} mm mercury. The focal spot has a diameter of 2-3 mm. It fluctuates from impulse to impulse and is displaced along the anode. It attains a range of 1-2 cm.

The generator described worked successfully for voltages of the order of 900 kV and was used in physical experiments.

69. Electrostatic generator

The operating principle of the high-voltage electrostatic generator is represented in Figure 189. A constant voltage source of 20-30 kV is connected to the edges C. The upward moving band B made of insulating material continuously obtains, through the corona, charges of a definite sign. Inside electrode A, charges are removed through discharge points F and cross over to the upper surface of the electrode. The electrode is charged to the voltage at which the current across the load (enclosed between electrode and ground) becomes equal to the inflow of charges.

Present-day electrostatic generators mainly are constructed for physical experiments. The greatest number of these give voltages up to 5-6 MV relative to the ground and represent gigantic structures 10-15 m in height. To decrease the dimensions, gaseous insulation under pressure is employed.

Individual generators are reserved for obtaining and using very strong x-rays. A 1-MV electrostatic generator of such type (relative to the ground) and current 3 mA operates under atmospheric pressure. The insulating column supporting the electrode is 3 m high. Charges are transferred along six bands 0.9 m wide, moved by a motor with velocity of about 2 m/sec. The total power required by the apparatus is 15 kw.

A generator of x-rays is the sectioned electron x-ray tube that operates with a pump. The tube is composed of 20 separate porcelain sections. In the places where the sections join are outlets of intermedial electrodes and special sealing is used. The tube is placed vertically. Length of the tube without anode is 3 m. The grounded anode emerges from a procedural location, situated under the base of the generator. Uniform distribution of voltage along the tube is attained with the aid of corona needle electrodes, set parallel to sections of the tube and joined to it by intermedial electrodes. The generator described has been used for deep x-raying for several years.

In another model of the electrostatic generator used for x-ray therapeutic purposes, of 1.25 MV voltage relative to the ground and 1 mA current, gaseous insulation under pressure is employed. /Literature 75/. Air was tested at 10 atm and freon at 3-3.5 atm. The generator, enclosed in a steel jacket 2.5 m high and 0.85 m in diameter, is situated vertically. A band 0.35 m wide moves with the same velocity as in the preceding model.

The x-ray tube is similar to the one described above; however, it is considerably shorter and has 16 sections. The anode of the tube is copper covered with gold. Uniform distribution of voltage along the tube is attained with the aid of multi-ohm voltage divider, set parallel to the tube and connected to the intermedial electrodes of the tube. The resistence of each section of the divider is 400 megaohms. Later, similar electrostatic generators were constructed with 2-MV x-ray tubes (relative to the ground) /Literature 76/.

In the Soviet Union electrostatic generators have been constructed for physical experiments. The perfection of electrostatic generators is proceeding at rapid pace, and it is possible in the not-too-distant future that they will also be used as superhigh-voltage generators of great power.

70. Betatron

In all the above-described installations for imparting great kinetic energy electrons it was necessary to apply to the tube total accelerating voltage. Constructional difficulties also have increased with the increase in voltage for which the installations were designed. Installations realized in practice, operating with voltages of the order of 5-6 MV relative to the ground, are very complicated and cumbersome. Meanwhile it is necessary for experimental physicists to accelerate electrons to energies many times surpassing 5-6 MeV. For this reason attempts have been made in recent years to create apparatuses in which electrons (and ions) would be given very great energies without the use of superhigh voltages.

In fact, is it necessary for the acceleration of charged particles to energies, for instance, of 20 MeV to have a total voltage of 20 MV?

Is it impossible to get along with considerably lower voltages, by impressing them on the path of the particles repeatedly? For the realization of this problem in the years 1927 - 1932 methods were proposed for the multiple linear acceleration of charged particles and multiple acceleration along a plane spiral. Without stopping to discuss these methods, we will state only that the method of acceleration along spirals received wide application in the so-called cyclotrons, which is used to accelerate positive ions.

The cyclotron, unfortunately, cannot be employed to accelerate electrons, possessing in comparison with ions a much smaller mass. The point is that the charged particles can be accelerated in the cyclotron only up to that point where there begins to appear a noticeable increase, with velocity, of the particle's mass. For energy of 2 MeV the velocity of the proton is 6.5% of the velocity of light and its mass exceeds the rest mass of the proton by 0.2%; but the velocity of an electron with energy 2 MeV equals 98% of the velocity of light, and its mass is approximately five times greater than the rest mass of the electron. For this reason, the electron could attain in the cyclotron an energy many times less than that which is imparted to it in superhigh-voltage charging tubes.

The efforts of physicists and engineers directed toward the discovery of a practical, suitable method of repeated acceleration of electrons were realized by the creation of an apparatus which received the name betatron [Literature 77 and 78]. At the present time, a betatron has been constructed in which electrons are accelerated to an energy of 100 MeV [Literature 79].

The operating principle of the betatron is based on the phenomenon of electromagnetic induction. Every variable magnetic flux causes a vortical electrical field, the closed lines of forces of which surround an induction current. In transformers this vortical electric field causes the appearance of electromotive forces in the windings. If the magnetic flux possesses an axis of symmetry, then the lines of force of the induced electrical field are represented by concentric circles, whose plane is perpendicular to the axis of magnetic flux, and the center coincides with the trace of the axis on this plane.

We assume that in the direction of a closed electric force line is situated a ring vacuum tube, in whose interior electrons move describing circles of constant radius (questions about what is the source of electrons, how the initial velocity is given them, and what holds them on an invariable orbit, remain for the time being unanswered). With increase of voltage of the magnetic field, a vortical electric field accelerates electrons. With every rotation the electron receives an increase in energy, equal to eU, where U is the instantaneous difference of potentials, which a voltmeter would show, if connected to one turn of wire located along the orbit of the electron.

This increase in energy, generally speaking, is not large. It can become very significant, however, if the electron performs many rotations. Theoretical calculations (taking into account the increase of mass with velocity) show, for example, that if the increase in energy after one rotation equals 20 eV and the magnetic flux varies uniformly, then for a diameter of orbit equal to 10 cm after one millisecond the total path traversed by the electron along the orbit is 290 km; that is, it performs 925,000 rotations and its kinetic energy increases by 18.5 MeV [Literature 78].

In this manner, with the aid of electromagnetic induction, it is possible to transmit to the electrons an extraordinarily large energy. For the practical realization of this idea, however, considerable difficulties had to be surmounted.

The most essential problem is the question - how can the accelerating electron be restrained on an invariable orbit. As is known, an electron falling with a certain initial velocity into a magnetic field, perpendicular to the direction of its motion, continues to move in this same plane, no matter how the trajectory of the electron's motion curves. This curving is greater, the greater the strength of the magnetic field. If the field strength increases, then the electron tends to move along the curve with decreasing radius of curvature. However, increase of the magnetic field strength causes, on the other hand, an increase of the electron's energy and momentum, as a result of which the radius of curvature should increase. From this it is possible to come to the conclusion that the change of the magnetic field can, obviously, be subjected to such a law for which these opposite tendencies compensate one another, as a result of which the electron will move along a curve of constant radius; that is, along a circle. Without carrying out the proof, we shall merely state that according to this law the strength of the magnetic field at points of equilibrium of the orbit must at every moment be two times smaller than the mean strength of the magnetic field in the interior of the orbit.

The condition indicated proved to be, however, insufficient for the successful acceleration of electrons. It is still necessary to find the initial conditions governing the electrons in order that they would fall on the equilibrium orbit.

Moreover, it was necessary to determine also the conditions of stability of the electron on an equilibrium orbit; traversing a path hundreds of kilometers long, every electron, even in a very well degasified tube, suffers collisions with many molecules. The conditions of stability must return after every collision the electron to the equilibrium orbit (we omit the formulation of the initial conditions and the conditions of stability of the electron on the equilibrium orbit). Only after the explanation of all these conditions did it prove possible to construct a practical suitable model of a betatron.

A betatron in which electrons are accelerated to a total energy of 2.3 MeV was made to show the possibility of accelerating electrons by electromagnetic induction, and data was obtained for the development of more powerful betatrons. It is small in size and is easily placed on a table (Figure 190). The 20-MeV betatron represents a considerably more sturdy installation. It is 1.5 long m, 0.5 m wide and 0.9 m high. The installation weighs about 3.5 tons. The 20 MeV betatron served, in particular, for investigating the possibility of practical utilization of the ultra-hard x-rays generated by it. The 100 MeV betatron is a colossal installation weighing 125 tons and is intended for physical experiments. The following description applies to the 20 MeV betatron.

Figure 191 shows the construction of a betatron. Between the poles of the electromagnet, fed by alternating current, is located a ring vacuum tube. The electromagnet in external appearance suggests a transformer of the drum-winding type. The conductor is constructed of separate sheets of transformer steel. Especially carefully constructed are the pole terminals. Here the steel sheets are arranged radially, which guarantees a perfect axis of symmetry of the magnetic field in the air gap. The electromagnet is fed from ~~the~~ an ac electric network ~~by an alternating current across~~ through ~~the~~ a static (magnetic) ~~triplicator of~~ frequency tripler. The feed power of the electro-[illegible] 26 [illegible].

Declassified in Part - Sanitized Copy Approved for Release 2012/04/17 : CIA-RDP82-00039R000100140018-7

magnet is 26 kW. In order to increase the power factor a resonance feed circuit is used. The capacitance of the battery of condensers is chosen of such a magnitude that the natural frequency of the oscillatory circuit obtained equals the frequency of the feed current (180 cycles).

In the first 20 MeV betatron, a ring vacuum tube was employed, made of glass and operated with a pump. Later it was replaced by a tube made from special porcelain, which permitted final evacuation to be performed at the time of manufacture.

The interior surface of the tube is covered with a thin silver layer with the aid of chemical silvering. This layer is grounded to prevent the accumulation of static charges on the surface of the tube, which charges could influence the movement of the electrons in the interior of the tube. At the same time, this layer possesses a sufficiently high resistance in order that vortical currents induced in it by the variable magnetic field of the electromagnet do not disturb the normal functioning of the apparatus.

An incandescent spiral filament serves as the source of electrons in the betatron. The spiral is surrounded by the accelerating electrode, to which is subjected a voltage of the order of 15-20 kV, necessary for giving the electrons their initial velocity. We note that the accelerating electrode is grounded and the spiral is placed under high voltage; otherwise the accelerating electrode would influence the circular motion of the electrons in the tube.

The betatron operates in the following manner. The magnetic field of the electromagnet varies sinusoidally. In the beginning of the period, from moment t_1 to moment t_2 (Figure 192) voltage is supplied to the accelerating electrode. The electrons thus accelerated are brought by the magnetic field of an electromagnet to an equilibrium orbit. This process lasts only the time (t_2-t_1), because the magnetic field must have a definite strength. For smaller field strength ($t < t_1$) the radius of curvature of the trajectory of the electron is too large; for larger field strength ($t > t_2$) the radius is too small. In consequence of this, the electrons would not fall on the equilibrium orbit, even if in this time an accelerating field were acting. They would only "clog up" the tube and impair the operating conditions.

In the course of time from t_2 to $T/4$ the electrons move along the equilibrium orbit, accelerating to energy 20 MeV. At the moment $t = T/4$, a current pulse is caused to pass through the complementary winding located on the electromagnet, thus changing the magnetic field. The radius of curvature of the electron orbit increases and the electron stream strikes against the target, thus creating an x-ray pulse. The current pulse can be displaced in time, thus forcing the electrons to abandon the equilibrium orbit sooner than the main field attains a maximum. In this case the electrons, naturally, decelerate to lower energies. The second, third and fourth quarters of the period are idle, after which the cycle repeats again. (Note: In 2.3 MeV and 100 MeV betatrons, the third quarter of the period is also active. In the course of this quarter the electrons move on the equilibrium orbit in the opposite direction. Also the pencil of x-rays emerge in the opposite direction).

The radius of the equilibrium orbit in the 20-MeV betatron equals 19 cm. In every cycle of acceleration the electrons perform about 350,000 revolutions, thus traversing a path about 420 km long. The mean current, with respect to time, on the target is calculated to be 1 microampere. At energies of 20 MeV, 65% of the kinetic energy of the electrons is converted into x-ray energy and only 35% into heat energy. For this reason the cooling of the target is not an essential problem.

As experiments show, the pencil of x-rays emanating from the target is sharply bounded in space within the limits of a cone with angle 6-7° at the vertex (Figure 1). This is very valuable for x-ray therapy. The power of the dose at a distance of 70 cm from the target attains 50 roentgens per minute. A second property valuable for x-ray therapy is the fortunate distribution of the doses in the depths of the biological object: the maximum dose lies at a distance of 3-4 cm from the surface.

Experiments in x-raying the parts of a machine, carried out with the aid of a 20 MeV betatron, have shown its complete applicability for this purpose [Literature 80]. According to a number of considerations which we cannot stop to discuss here, it is scarcely expedient in practical x-raying to apply the x-rays generated by electron energies surpassing 20 MeV. Even now such betatrons are not too cumbersome. In the next few years we can expect their further perfection and wide-spread use for purposes of x-ray therapy and x-raying of materials.

As for physical experiments, here the efforts of physicists and engineers are directed toward magnifying further the energy of the accelerated particles. To accelerate electrons to energies higher than 100 MeV, new systems of acceleration are proposed, chiefly the synchrotron, whose operating principle was first proposed by the Soviet scientist V. I. Veksler. Reader desiring to become acquainted in more detail with this problem are recommended to read the published work on the acceleration of charged particles by Professor A. A. Vorobev.

THE LITERATURE USED IN COMPILING CHAPTER VII

69. A. V. Filippov and V. V. Yainskiy, "A 500,000-volt X-Ray Installation", Uspekhi Rentgenotekhniki, No. 1, Moscow, 1937.

70. E. E. Charlton, W. E. Westendorp, L. E. Dempster, and G. Hotaling, "A New Million Volt X-Ray Outfit", J of Applied Physics, Vol 10, No. 6, 1939.

71. Charlton and Westendorp, "A Portable Million-Volt X-Ray Outfit for Industrial Laboratories", GER, Vol 44, No. 12, 1941.

72. E. M. Gokhberg, "Elegas, An Electrical Gaseous Insulation", Elektrichestvo, No. 3, 1947.

73. Charlton and Westendorp, "Mobile Industrial X-Ray Unit", Electronics, December 1944.

74. F. F. Lange and L. I. Pivovar, "Compact Million-Volt Apparatus", Izvestiya Akademii Nauk SSSR, Seriya Fizicheskaya, Vol IV, No. 2, 1940.

75. J. G. Trump and R. J. Van de Graaff, "A Compact Pressure-Insulated Electrostatic X-Ray Generator", Physical Review, Vol 55, No. 12, 1939.

76. W. W. Buechner, R. J. Vande Graaf, et alii, "Electrostatic Accelerator for Electrons", Review of Scientific Instruments, Vol 18, No. 10, 1947.

77. D. W. Kerst, "Betatron", Uspekhi Fizicheskikh Nauk, Vol 26, No. 2, 1944.

78. A. P. Grinberg, "Acceleration of Electrons by Electromagnetic Induction (Kerst's Betatron)", Uspekhi Fizicheskikh Nauk, Vol 27, No. 1, 1945.

79. W. Westendorp and E. Charlton, "Induction Accelerator of Electrons to 100,000,000 Volts /translation of an English language article into Russian/", Uspekhi Fizicheskikh Nauk, Vol 30, Nos 1-2, 1946.

80. J. P. Girard and G. D. Adams, "Application of the Betatron to Practical Radiography", Electrical Engineering, Vol 65, No. 5, 1946.

/Note: Figures follow./

APPENDIX

Figure 180. Sectioned electron tube of 500 kV_{max}.

1 - cathode
2 - intermedial electrode
3 - hollow anode
4 - wolfram mirror (target)
5 - water jacket
6 - lead hood
7 - focussing coil winding

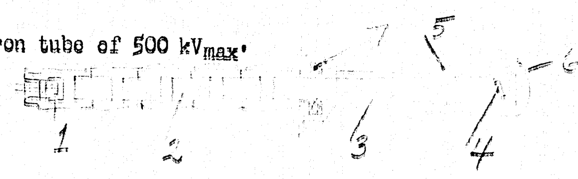

Figure 181.

X-ray tubes of one and two million volts.

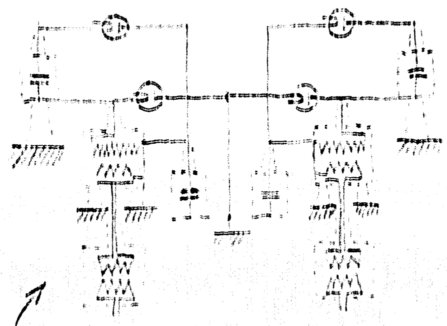

Figure 182. Schematic diagram of a Soviet-made 500-kV_{max} apparatus.

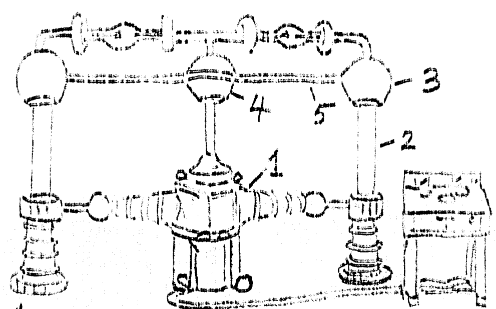

Figure 183. A 800-kV_{max} apparatus.

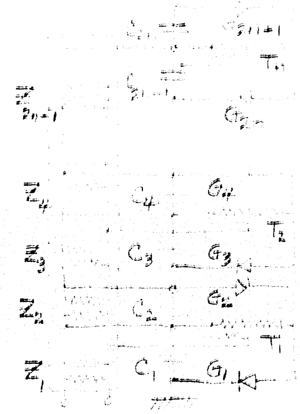

Figure 184. Schematic diagram showing an installation of one million volts relative to the ground with cascade connection of the voltage-doubling circuit.

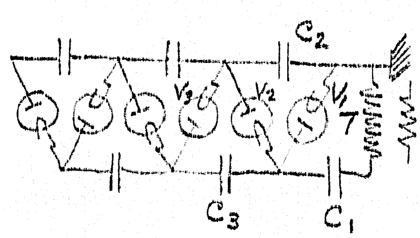

Figure 185. Schematic diagram showing repeated (multistage) voltage-multiplication.

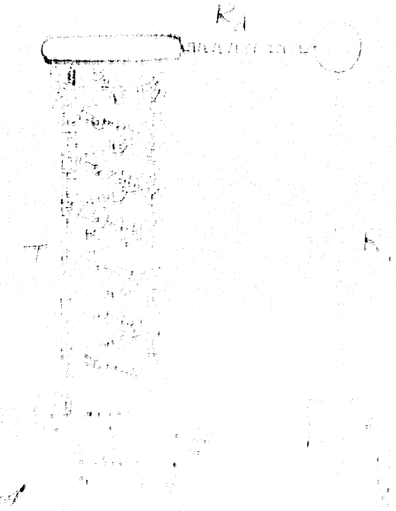

Figure 186. Schematic diagram showing an installation of 1.25 MV relative to the ground, built according to the multiplication circuit scheme.

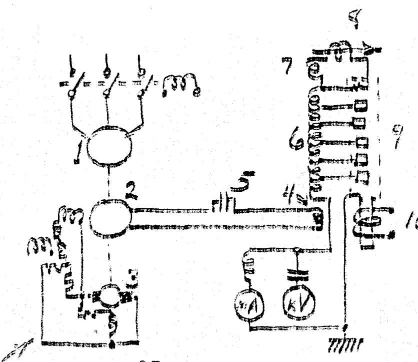

Figure 187. Schematic diagram showing an installation of 1 MV relative to the ground, with a resonance transformer.

1 - motor
2 - generator of triple frequency
3 - exciter
4 - primary winding of resonance transformer
5 - capacitance
6 - secondary winding of resonance transformer
7 - heater winding (coil)
8 - choke coil
9 - sectioned x-ray tube
10 - focussing coil.

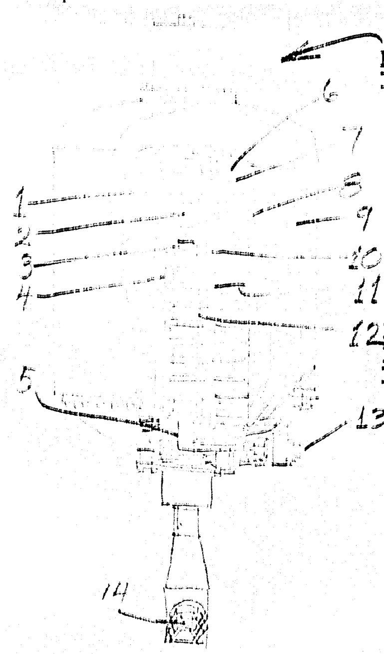

Figure 188. Sketch showing a block transformer of 1 MV relative to the ground.

1 - cathode of the x-ray tube
2 - intermedial electrodes of the x-ray tube
3 - " " " " "
4 - vitreous tie bolt
5 - primary winding
6 - heater regulation choke-coil
7 - heater winding
8 - secondary winding
9 - steel armature
10 - insulating device of the heater choke-coil
11 - outlet of the intermedial electrode
12 - glass envelope of the x-ray tube
13 - motor for operating heater regulation
14 - anode of the x-ray tube

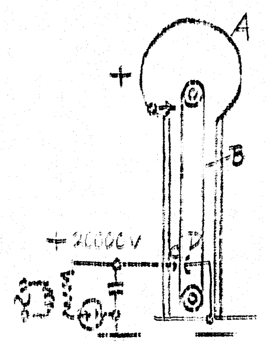

Figure 189. Schematic diagram showing the principle of operation employed by the Van de Graaff electrostatic generator.

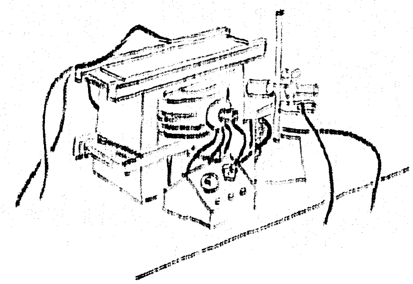

Figure 190. A 2.3-Mev betatron.

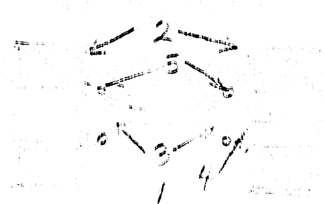

Figure 191. Principle of construction employed by the betatron.

1 - core of the electromagnet
2 - main magnetizing winding
3 - circuline vacuum tube
4 - source of electrons
5 - supplementary displacing winding.

Figure 192. Curve illustrating the operation of the betatron (see the text).