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A HIGH VOLTAGE X-RAY INSTALLATION

BY

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For several years the development in the production of X-rays for medical deep therapy has been governed by the demand of an increased depth dose. This has mainly been achieved by increasing the voltage, although the second alternative, increasing the current, has also been proposed. In the latter case the increase in depth dose is obtained merely as a result of the increase in intensity, which allows a larger distance from the anode to the skin, in the former both the intensity and the penetrability of the X-rays are increased. A closer consideration shows that a limit to the energy which can be applied to the anode, is soon set by the difficulties encountered in the cooling; since, however, the output of X-rays is nearly proportional to the third power of the voltage, a rapid increase of the intensity of the X-rays can be obtained by increasing the voltage without at the same time increasing the energy applied to the anode.

The development in the construction of high voltage X-ray installations which has taken place during the last 10 or 15 years, has been intimately connected with the progress in the experiments on nuclear physics. The X-ray tubes are in most cases built in the same general way as the accelerating tubes used for nuclear research; the high voltage sources show a great variety, both electrostatic high voltage (1), (2), (3) transformers with rectification (4) or without rectification (5), (6), (7) have been used.

The design to be described here employs unrectified a. c. voltage from a resonance transformer (2) giving a simple and compact construction. The use of unrectified voltage on the other hand gives a somewhat smaller output of X-rays than a d. c. voltage. This point is considered in more detail below.

The high voltage source is a resonance transformer, where the secondary coil is built from 95 flat coils stacked on each other, separated by 6 mm. intervals for ventilation, the axis of the coil is vertical. Each of the flat coils contains 1,600 windings of 0.2 mm. copper wire, the dimensions of the winding area are height 3 mm., inner and outer diameter 45 cm. and 60 cm. Each of the flat coils is supported by a ring of cardboard, which extends about 2 cm. beyond the outer and inner edge of the winding, the whole being pasted together with paraffin wax[1]. The primary coil, wound from flat copper band, is placed below the secondary one. On top of the secondary coil is placed a hemispherical shield made of zinc.

The transformer is placed in a pressure tank with diameter 1.7 metres and height 2.7 metres. The tank is filled with carbon dioxide to a pressure of 3 atm.; carbon dioxide is used instead of air to prevent the insulating materials from catching fire. The tank is made in two parts, which are bolted together. The top part can be lifted by a crane.

To prevent losses in the wall of the pressure tank a laminated steel shield is placed inside the tank, the shield extends to the same height as the hemisphere on top of the transformer. The distance between the secondary coil and the inside of the laminated shield is 39 cm. When the tank is filled with carbon dioxide, a pressure of 3 atm. is sufficient to prevent sparking over at a voltage of 900 kV. The resonance frequency is 300 Hz. The current for the primary coil is delivered by a rotating converter driven by 250 volts d. c., which in turn is delivered by a second converter driven by 380 volts a. c. from the city mains. The speed of revolution of the a. c. generator connected to the primary coil can be varied by a resistance placed in the magnetizing circuit of the d. c. motor driving it, so that the frequency of the a. c. generator can be tuned to resonance with the transformer. The mechanical inertia of the rotors of the two con-

[1] The use of paraffin wax and cardboard involves relatively high dielectric losses; because of the war situation low loss materials such as mica were unobtainable.

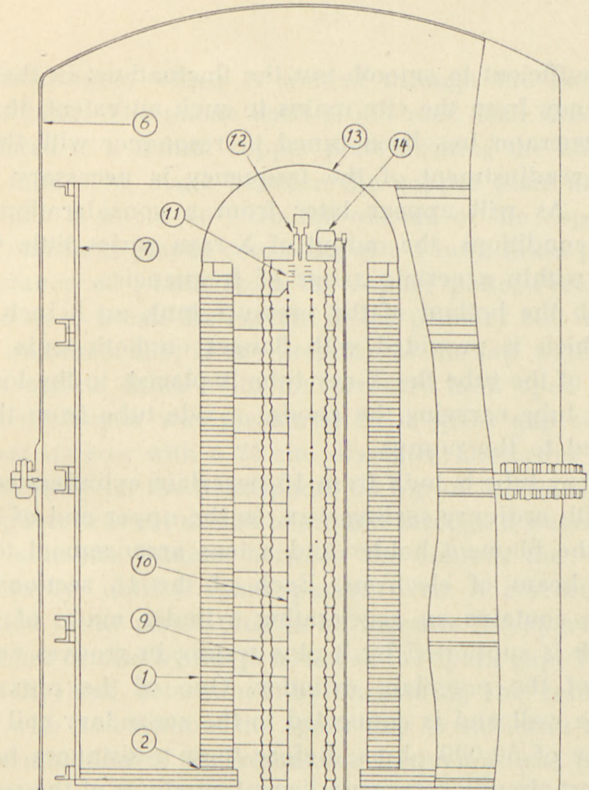

Fig. 1. (1) secondary coil. (2) primary coil. (3) cardboard rings. (4) secondary coil. (5) intermediate insulator for separating the coils. (6) pressure tank. (7) laminated shield. (8) steel tube. (9) porcelain cylinder. (10) accelerating electrode. (11) lens arrangement. (12) filament holder. (13) hemisphere. (14) variable choke.

verters is sufficient to smooth out the fluctuations in the voltage and frequency from the city mains to such an extent, that when once the generator has been tuned to resonance with the transformer, a readjustment of the frequency is necessary only in rare cases. As will appear later from a consideration of the resonance conditions, the output of X-rays varies little with the frequency within a certain range of frequencies.

Through the bottom of the pressure tank an 8 inch tube is welded, which is provided with flanges on both ends. On the upper end of the tube the X-ray tube is placed, to the lower end is bolted a tube carrying the anode; a side tube from the latter is connected to the pumps.

The X-ray tube is built from 15 porcelain cylinders cemented together with ordinary sealing wax. In the upper end of the tube is placed the filament holder and a lens arrangement to obtain a parallel beam of electrons. Each of the 15 sections of the X-ray tube contains an accelerating cylinder made of stainless steel, which is supported by 3 pins resting in grooves cut in the end face of the porcelain cylinder. One of the pins extends through the wall and is connected to the secondary coil through a resistance of 50,000 ohms. Before these resistances had been placed, short circuits between adjacent windings of the secondary coil frequently occurred, probably caused by high frequency oscillations set up when a spark passed over inside the X-ray tube.

The current for the filament is taken from a coil with 12 windings placed on top of the secondary coil. The current is regulated by a variable choke, the regulation being carried out by turning an insulating rod, which extends through a gasket in the bottom of the pressure tank.

The pressure tank with the laminated steel shield is shown partly in section in Fig. 1, which also shows the secondary coil with the X-ray tube placed in the axis.

The pumping arrangement consists of a 5-inch and a 2-inch single stage oil diffusion pump connected in series and backed by a rotating pump. Under ordinary working conditions the pressure as measured by a McLeod gauge connected to the system near the pumps is about 10^{-6} mm.

The anode is placed at the bottom of a copper tube connected to the steel tube, which is welded through the bottom of the pressure tank. The anode itself is a 1 mm. lead sheet, which is tin soldered to a 2 mm. copper plate forming the bottom of the copper tube. The angle between the copper plate and the axis of the tube is about 70°. On the outside of the copper plate a cooling mantle is placed consisting of a 1 mm. brass plate placed at a distance of 1 mm. from the copper plate. Precautions are taken so as to break the current in the primary coil of the transformer automatically, if the pressure of the tap water decreases below a certain limit. With the pressure tank open the voltage of the transformer was measured by a spark gap consisting of two brass spheres with a 25 cm. diameter; the lower sphere was placed directly on the hemisphere on top of the transformer, the upper sphere was connected to ground through a water resistance. With a suitable distance between the spheres the voltage was raised slowly, until a spark passed over. A correction had to be applied to the results due to an increase in capacity of about 10 per cent. caused by the presence of the spark gap. The increase in capacity was determined by measuring the resonance frequency with and without the spark gap. A sufficient accuracy in the determination of the resonance frequency was obtained by the use of a phonic wheel connected to a counting meter. As a result it was found that for a current of 1 mA in the secondary coil the voltage is 9.0 KV peak value.

For voltages below 250 KV where the spark gap could be used, the voltage was found to be proportional to the secondary current; this may safely be assumed to hold good for higher currents, too, because the influence of the laminated steel shield on the magnetic field of the transformer is small, so that the inductance of the coil is independent of the load. A separate voltmeter for the determination of the high voltage is thus unnecessary, the voltage being read on an a. c. instrument placed in the line connecting the lower end of the secondary to ground.

The magnetic field of the secondary coil is, as usual in a solenoid, strongest near the middle and decreasing against both ends. The voltage generated per unit length of the coil was measured by placing a single turn of a stiff copper wire round the coil and short circuiting the ends through an a. c. ammeter; the current in the ammeter was read with the copper wire placed at different heights, the current in the coil being kept constant. The results are shown in Fig. 2; it is seen that the maximum and minimum voltages differ by about 25 per cent. from the mean value.

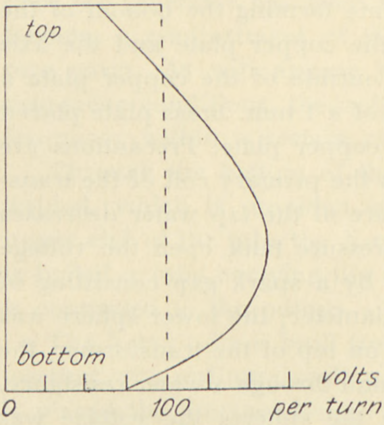

Fig. 2.

An important question for the use of the transformer is the rise in temperature of the secondary coil, since this obviously sets a limit to the time interval during which the transformer can be used continuously. A determination of the mean rise in temperature can be made with the pressure tank closed by pushing a brass rod (not shown in Fig. 1) through a gasket in the wall of the pressure tank, until it makes contact with the metal hemisphere; the mean temperature of the coil can now be determined by measuring the resistance. For a more detailed knowledge it is necessary to determine the temperature rise at various points of the coil; this was done with the pressure tank open. The results are shown in Fig. 3, showing both the rise in temperature at various heights of the coil and the mean value. If the maximum permissible rise in temperature is fixed at 20° C., the measurements show that the corresponding mean rise in temperature will be 14°, or a change in the resistance of 5.3 per cent. The rise in temperature found in actual use, where the apparatus is always used intermittently, hardly exceeds half of this. No measurements of the rise in temperature with the apparatus running continuously have so far been made.

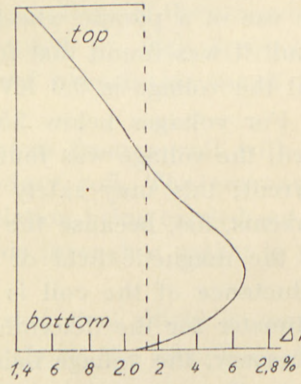

Fig. 3.

In Fig. 4a is shown the secondary current as a function of the frequency, the voltage applied to the primary coil being kept constant. From the curve it is found that $Q = \omega L : r_{\text{eff}}$ is 22, where r_{eff} is an effective resistance of the circuit, including all the losses. ωL is found from $V = i \cdot \omega L$, where V and i are effective values of voltage and current in the secondary coil. With 9.0 KV peak value per milliamp. as found previously, ωL becomes 6.3×10^6, or $r_{\text{eff}} = 2.9 \times 10^5$ ohms. Since the resistance of the secondary coil is 1.35×10^5 ohms, a considerable part of the losses are of dielectric origin.

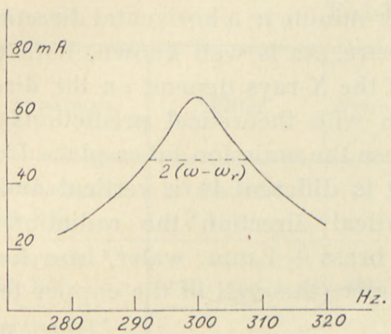

Fig. 4 a.

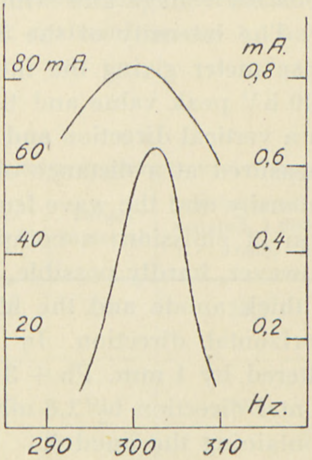

Fig. 4 b.

In Fig. 4b are shown the secondary current and the emission from the filament as a function of the frequency. From the variation of the emission current it is seen, that to keep the emission sufficiently constant the frequency must be kept constant within less than 0.5 per cent. As already mentioned, the mechanical inertia of the rotating converters is sufficient to eliminate fluctuations of short duration in the supply from the city mains. It is seen that the maximum of emission from the filament occurs at a slightly higher frequency than the maximum of the secondary current, as was to be expected, because the filament voltage is proportional both to the secondary current and to the frequency. Inside the region of frequencies which lies between the two maxima, the changes in filament current and in the secondary voltage, resulting from a change in frequency, are in opposite directions. This means that the dependence of the output of

X-rays on the frequency is less critical than might appear from a consideration of the emission current alone.

For the purpose of screening the anode is surrounded by a cylindrical lead block with ports for a vertical and a horizontal beam of X-rays. The accessories for use in the X-ray treatment will be described elsewhere, together with the results obtained from measurements carried out in connection with the actual treatment; in this connection the output of X-rays obtained with constant voltage and with alternating voltage will be discussed.

The intensity of the X-rays was measured with a Siemens dose meter giving the intensity in r per minute directly. With 900 KV peak value and 1 mA the intensity was 21 r per minute in a vertical direction and 8 r per minute in a horizontal direction, measured at a distance of 1 metre. As is well known, both the intensity and the wave-length of the X-rays depend on the direction of emission; a comparison with theoretical predictions is, however, hardly possible, because the emission takes place from a thick anode and the filtering is different in a vertical and a horizontal direction. In a vertical direction the radiation is filtered by 1 mm. Pb + 3 mm. brass + 1 mm. water, in a horizontal direction by 2.6 mm. copper (the wall of the copper tube containing the anode).

The output of X-rays obtained with alternating voltage is of course smaller than with constant voltage under the same conditions, i. e. the same maximum voltage and the same current. If it is assumed that the output of X-rays is proportional to the third power of the voltage, a simple consideration shows that the output per milliamp. with constant voltage should be 2.3 times that obtained with alternating voltage. To obtain more definite information the results shown in Table 1 have been collected. In these measurements both the voltage and the filtering have varied considerably, so that corrections must be applied to make the results comparable. For the variation with voltage it will be assumed here that the output is proportional to V^n with $n = 3$; this agrees quite well with the results for the variation of output with voltage, although for a heavy filtering a slightly higher value of n would be preferable. To correct for the variation in filter thickness the results given by Haenisch, Lasser, Eisl, and Rump (4) have been used. They measured the absorption in different materials for 1000 KV X-rays; with the aid of their results it is easy to refer the results to a standard filter thickness, provided the same absorption curves can be used in the range of voltages between 900 and 1500 KV. In Table 1 the results as given by the authors have been recalculated to correspond to a filter of 5 mm. Pb and 1000 KV.

A further correction is that due to the differences in target material. This has not been included in Table 1, partly because it is of minor importance and partly because no determination of the variation of output with target material seems to have been carried out.

Table 1.

Apparatus	Filter	r/min	Filter equiv. Pb	Target material	r/min. recalculated 1.000 KV. 5 mm. Pb
Electrostat.[1] 1000 KV.	3.3 Pb + 5 Cu + 2 Al	24	5.3	Au	25.3
Electrostat.[2] 1250 KV.	2 Pb + 5 Cu	62	3.7	Pb	26.0
Electrostat.[3] 1500 KV.	10.5 Pb	60	10.5	Pb	36
Transform.[4] 1000 KV. rectif.	5 Pb	37	5	W	37
Transform.[5] 1000 KV. unrectif.	1.5 W + 4.75 Ni + 15.7 brass	5.6	10.1	W	10.9
Transform.* 900 KV. unrectif.	1 Pb + 3 Cu	21.2	2.0	Pb	17.2

Intensity in r/min at 1 milliamp. and 1 meter distance; no correction for difference in target material. *Present determination.

The results given in the last column show that the ratio between the output obtained with constant voltage and with alternating voltage probably is not far from the value 2.3, which was estimated previously, but at the same time the results are so widely scattered, that a direct comparison hardly seems justifiable. From the corrections introduced the correction for the variation in filter thickness is likely to introduce a slight error, because the same absorption curves have been used at different voltages; this does not explain the difference between the results quoted under (1) and (4), which have been obtained under nearly identical conditions. The same applies to the results (5) and (6), although the difference in filter thickness here is considerable. Dahl and Trumpy working with 1.5 MV, d. c. and a filter of 10.5 mm. Pb find half a value layer of 6.8 mm. Pb, a value which fits fairly well into the absorption curve for 1000 KV radiation given by Haenisch, Lassen, Eisl, and Rump. This agreement between values for the absorption in lead obtained under rather different conditions indicates that the error introduced by using the same absorption curves at different voltages is insignificant.

As regards the ratio (d. c. output) : (a. c. output), the results can be arranged in two groups, one containing the results (1), (2), and (5), giving the ratio 2.3, and a second group (3), (4), and (6) giving the ratio 2.1. The differences between the two groups are, however, so large, that they cannot possibly have been introduced by the corrections for filter thickness and voltage.

We have here considered the output as a function of the voltage for a constant current through the X-ray tube. It is probably more interesting to consider the output obtained when the energy supplied to the X-ray tube is kept constant, since it is the difficulties in the cooling of the anode which will usually set a limit to the output of X-rays. If this is done, the calculated ratio of 2.3 must be divided by $\sqrt{2}$, giving 1.6.

A quite considerable gain in intensity is thus obtained by the use of constant voltage, a gain which must be confronted with the simplicity and compactness of design of an apparatus employing alternating voltage.

The building where the X-ray tube is installed, is shown in ground plan and in section in Fig. 5a and b. The pressure tank is placed on the upper floor with the anode tube extending into the treatment room. The height of the pressure tank is 2.7 metres, the height of the room 4 metres. Besides the treatment room the ground floor comprises a control room and a machine room. The thickness of the wall, ordinary brick wall, between the

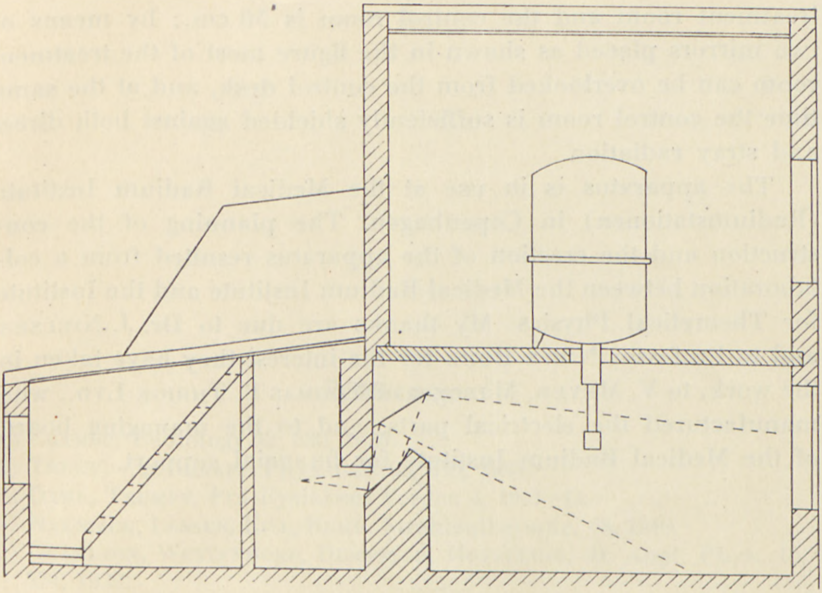

Fig. 5 a.

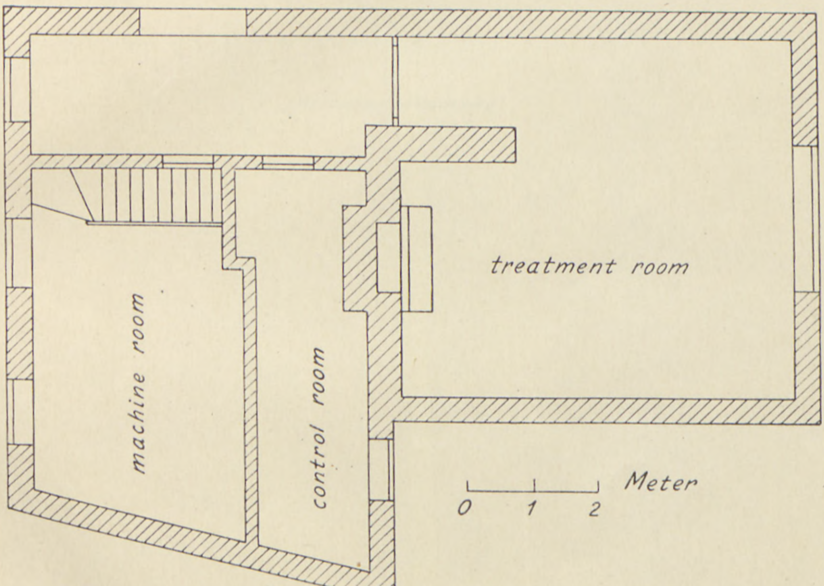

Fig. 5 b.

treatment room and the control room is 50 cm.; by means of two mirrors placed as shown in the figure most of the treatment room can be overlooked from the control desk, and at the same time the control room is sufficiently shielded against both direct and stray radiation.

The apparatus is in use at the Medical Radium Institute (Radiumstationen) in Copenhagen. The planning of the construction and the erection of the apparatus resulted from a collaboration between the Medical Radium Institute and the Institute for Theoretical Physics. My thanks are due to Dr. J. Nielsen and to Professor Niels Bohr for the interest they have taken in the work, to V. Meyer, Manager of Thomas B. Thrige Ltd., who manufactured the electrical parts, and to the managing board of the Medical Radium Institute for financial support.

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