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A Radiofrequency High-Voltage Generator

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A large radio oscillator with unrectified alternating anode power-supply sends high-frequency power into a 50 meter wave-length antenna which is coiled up without insulation, and enclosed in a metal vacuum tank. Over 800,000 volts is generated inside of the tank exactly where it is to be used for x-rays or for accelerating ions. There is no insulation to become punctured. Single tuned-circuit resonance transformers are superior to coupled tuned-circuit Tesla coils. Resonance transformers, oscillator circuits, power tubes, power supply and coil construction are described. X-ray production, and ion acceleration are outlined.

THE insulation of vacuum tubes is a serious problem in their adaptation to extremely high voltage. A method is here described for generating a very high voltage entirely inside the vacuum tube in which it is to be used. Short-wave high-power radio technique makes possible a resonance transformer whose high-voltage secondary consists of only ten to fifteen turns of heavy copper pipe, entirely free from insulating material, and internally water-cooled. The surrounding copper wall inside the evacuated steel tank is the support for the grounded voltage-node of the coil, thus placing the free high-voltage end in the vacuum exactly where it is to be used. Failure of insulation is positively avoided by the completely metallic construction.

RESONANCE TRANSFORMERS

Radio oscillator tubes are used to generate the high voltage in a resonant circuit. Two general classes of circuits are possible. The first class consists of coupled separately-tuned resonant circuits, such as the Tesla coil. They are not satisfactory because of their low efficiency. The second and only practical class of circuits for this high voltage generator consists of single tuned resonant circuits, hereafter called resonance transformers. The term "resonance transformer" accurately characterizes the behavior of a single resonant circuit, insofar as the transfer of power from one section of the circuit to another is concerned, provided that the frequency is exactly the resonant frequency, and the power is less than about 10 percent of the circulating kilovolt-amperes. In this usage, the selectivity of the circuit is of no intrinsic importance. While a resonance transformer may consist of several mechanically separated sections, such as a primary and a secondary coil, the sections must act as a single resonant circuit. The effective constants of such a composite circuit, oscillating as a single unit, include the constants of all the branches interacting upon each other. Although a connection diagram of such a composite form of the singly tuned circuit of a resonance transformer may happen to look exactly like the diagram of coupled separately tuned circuits, the constants are such that an entirely different system of oscillations is produced.

This is a vital distinction, because the first mentioned class of circuits, separately tuned and coupled together, such as the Tesla coil, cannot give more than 50 percent efficiency of energy transfer from primary to secondary when driven by a self-excited oscillator tube, because of the extremely loose coupling needed between low resistance tuned circuits.

Resonance transformer superior to Tesla coil

If two resonant circuits having resistances R_P and R_S, respectively, are tuned to the same frequency f, and the coupling between the circuits consists of mutual inductance M, then the critical coupling is $2\pi f M=(R_P R_S)^{\frac{1}{2}}$. The efficiency of energy-transfer from one circuit to the other increases as M is increased, until at critical coupling an efficiency of 50 percent is reached. Further increase of coupling establishes two new stable frequencies, each of which retains this same efficiency.

Although the efficiency for the original frequency continues to increase as the coupling is increased beyond the critical value, this frequency is now unstable and cannot be used by a self-excited oscillator. Instead, a self-excited vacuum tube will oscillate at one of the stable new inferior frequencies. Detuning one circuit favors one of these frequencies and raises the limiting efficiency slightly above 50 percent. But to adhere to the original unstable secondary frequency and obtain high efficiency by closely coupling the two tuned circuits, it is necessary that the tubes be neutralized non-regeneratively, and be driven by a master oscillator or by excitation obtained directly out of the separately tuned secondary circuit.

On the other hand, a resonance transformer operates as a single unit of inductance and capacity in spite of possible physical sub-division into separated, but coupled, sections. It has only one frequency of oscillation (aside from harmonics), and is ideal for self-excited vacuum tube operation. Energy is transferred from the primary to the secondary portion of the single oscillating system of the resonance transformer with an efficiency close to 100 percent. Clearly then, a high voltage can be generated in a resonant circuit functioning as a resonance transformer twice as efficiently as when operated as a Tesla coil, when continuously driven by a self-excited vacuum tube. Moreover, the resonance transformer construction is enormously simpler than that of a Tesla coil, because the latter has extensive stray magnetic fields arising from the very loose coupling which low-resistance tuned circuits require with a self-excited oscillator.

Moreover for other reasons, the conventional Tesla coil, when using spark excitation, is even less satisfactory for vacuum operation. A spark excited resonance transformer cannot generate a high voltage, because the coil cannot respond as a unit to the transient discharge of the condenser connected across a small portion of it. This exclusion of the resonance transformer is no drawback, for with spark excitation the energy is transferred from the separately tuned primary into the tuned secondary of the Tesla coil quite efficiently by using coupling much closer than the critical value which could be used with vacuum tube self-excitation. With suitably close coupling of the two tuned circuits, the two new frequencies which are established cause the energy to drift from primary to secondary and back at the frequency of the beat between the two frequencies. Proper quenching of the spark leaves all of the energy in the secondary, transferred there from the primary at quite high efficiency. Too much of this energy, however, is uselessly dissipated in the tail of the damped wave train. The high voltage occurs only during a very small portion of the total time. In order to impart adequate energy to the system, the necessarily large primary condenser, which stores energy preparatory to oscillating, sets a low frequency that requires a secondary of many turns of small wire. This is a serious disadvantage, for such a coil of small wire is difficult to cool in a vacuum and cannot be provided with an adequate insulating support.[1]

Oscillator Circuit

Any type of radio oscillator may be coupled to a resonance transformer by a high-frequency transmission line, but very few oscillators can be connected directly into the high-voltage resonance transformer. The Hartley circuit is adapted only to driving a resonance transformer having a high voltage step-up in applications where the inductance, which should float at grid bias potential with no voltage node at either end, is readily accessible for adjustment of its connections. Only the "tuned-plate tuned-grid" circuit is suited to driving directly a resonance transformer enclosed in a metal tank. The power output of the single-tube oscillator circuit, Fig. 1(a), is definitely limited by overheating of the

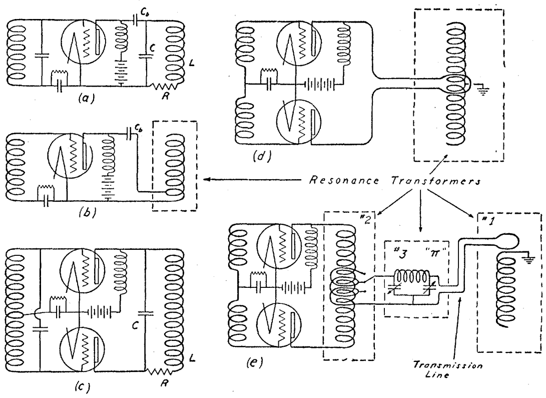

FIG. 1. Resonance transformer connections to oscillator tubes.

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[1] Kossel and Eckhardt, Ann. d. Physik **17**, 543 (1933).

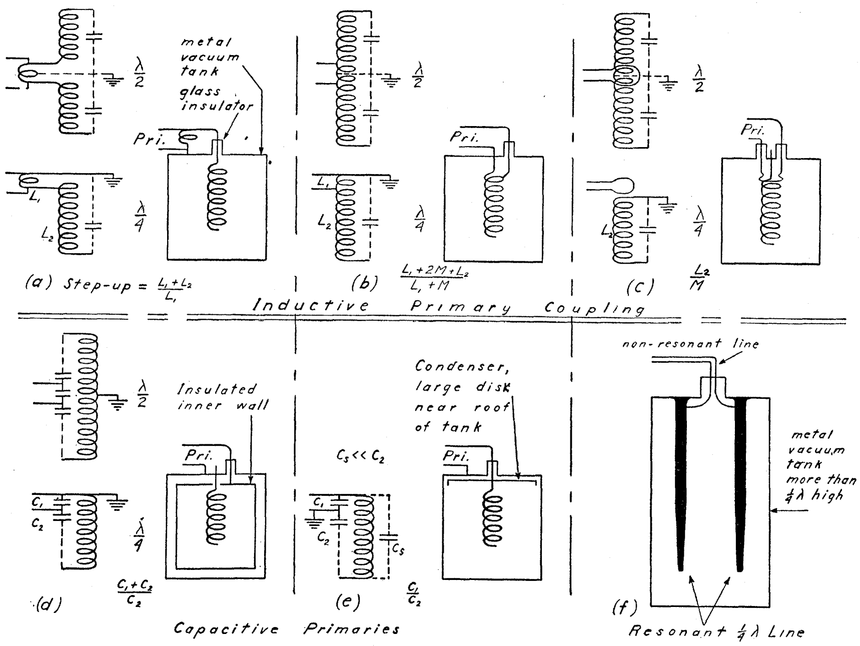

FIG. 2. Types of high-voltage resonance transformers.

condenser C_b that is used in the external high-frequency path between anode and cathode to insulate the direct anode voltage from the cathode. Hence only push-pull type oscillators are used, Fig. 1(c), because they require no such insulating condenser.

To eliminate a troublesome parasitic oscillation, only the grid input capacity is used in tuning the grid circuit, Figs. 1(b–d–e). The tuning of the grid circuit is performed by stretching the grid inductance coil. Another parasitic oscillation is eliminated by greatly reducing the mutual inductance between the two inductance coils which tune the two grid-circuits of the particular push-pull arrangement for Fig. 3.

It is important that the anode output capacity of the tubes contribute to the total capacity C that is effective in any resonance transformer connected directly to the tubes in *exactly the same manner* as it contributes to the output circuit LCR of Figs. 1(a) or 1(c). Otherwise, in Fig. 1(b) for example, if the anode capacity and the primary portion of the inductance resonated near the natural frequency of the rest of the transformer, the circuit would resolve itself into inefficient coupled resonant circuits.

With high power oscillator tubes, the physical dimensions of the leads of Fig. 1(d), for example, are not negligible compared to the operating wave-length. The leads themselves, which connect the oscillator anodes directly to the resonance transformer, act as a transmission line having waves reflected at its ends. The impedance varies along such a line, and may even be utilized in some cases to match the impedance of the oscillator tubes to the resonance transformer.

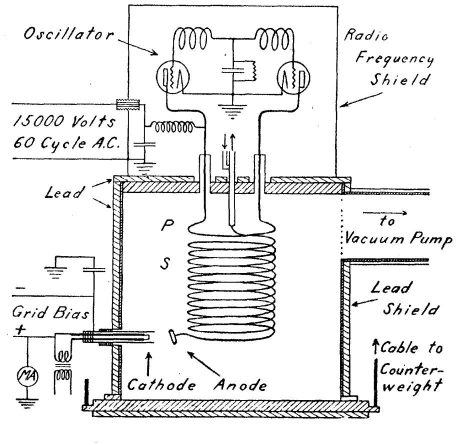

FIG. 3. X-ray arrangement with inductive primary separated from the high-voltage coil.

If the leads are very short, however, the energy in their fields is insufficient to disturb the system even when their behavior as a line is ignored.

The simple output circuit of Fig. 1(c) is actually replaced by a more complex resonance transformer, Figs. 1(d), 1(e), which may be one of the types from Fig. 2, used either to step the voltage up directly, or to step it down to match an intermediate transmission line. The intermediate line is essential for connecting the oscillator to the second class of resonance transformers mentioned below, as these transformers are $\frac{1}{4}\lambda$ resonant lines of the Lecher wire type, Fig. 2(f).

Types of Resonance Transformers

Resonance transformers consist of parallel resonant circuits which may be grouped into three classes, characterized first by "lumped" constants, secondly by evenly distributed constants, and thirdly by unevenly distributed constants plus mutual induction between elements of the circuit. Only the latter two types are of practical value for generating high voltage, the third type being especially compact and simple to adjust.

First, the "lumped constants" type has a capacity C connected across an inductance L in series with a resistance R. If R is evenly divided between the L and C branches, the impedance Z which the parallel resonant circuit offers to an e.m.f. of resonant frequency, applied across L, is a pure resistance $R' = L/RC$, being neither inductive nor capacitive at the resonant frequency. This expression is nearly true for ordinary tuned radio circuits, which by careful low-loss construction may have R' equal to about a million ohms. However, a high-voltage resonance transformer requires several million ohms impedance, which is obtained by enlarged dimensions and elimination of all C except the distributed capacity, which then results in the third class of transformer. For simplicity, the first class, with lumped constants, is assumed in approximating the step-up ratios listed with the various types in Fig. 2. M is the mutual inductance between the primary L_1 and the main inductance L_2. These voltage step-up ratios are the square-roots of the ratios of the total impedance to the primary impedance at the resonant frequency.

The second class of resonance transformers, with distributed constants, is the most efficient, but is much too expensive to build. These consist of $\frac{1}{4}\lambda$ transmission lines, open at one end and short circuited at the other, Fig. 2(f). In spite of their low ratio of L/C, the open end impedance $R' = 2L/RC$ may attain enormous values because R can be made exceedingly small by using conductors of very large diameter. The exact expressions for the impedance of the open end as well as for the primary portion of the line may readily be obtained from texts on transmission line theory.

The third and most useful class of resonance transformers, having mutual inductance between elements of the circuit in addition to having the capacity unevenly distributed along the inductance, cannot be treated usefully by mathematics. The types in Fig. 2 are of this class, in actual high-voltage applications. When adjusted to maximum step-up the primary impedance is approximately equal to that of the oscillator anodes, but even the output impedance of "class C" oscillators is rather indefinite. Moreover, even if it were known, the step-up ratio is not important for quantitative use because the input voltage is very difficult to determine.

Voltage measurements

The total voltage generated by the resonance transformer is obtained roughly by the relation $W = E^2/R'$, from a measurement of the watts, W, generated in the coil whose resonant impedance R' is known only approximately. It is also easy to measure a known fraction of the generated r.m.s. voltage, but neither of these direct methods are dependable because the wave-shape due to the non-linear modulation by the unrectified anode supply-voltage is difficult to determine for each new adjustment. The known fraction of the generated voltage could be determined accurately with a peak-voltage vacuum tube voltmeter, but a more concise voltage measurement would result from a measurement of the maximum energy of photoelectrons ejected by the x-rays that arise when the coil is struck by electrons from gaseous currents or from an x-ray cathode.

It is simpler, however, to filter these x-rays through a centimeter or more of lead and plot an aluminum absorption curve from which the absorption coefficient per electron is obtainable, and with the Klein-Nishina formula the effective wave-length of the x-rays is found, and from this the voltage of the x-rays is directly obtainable. X-rays of these energies are absorbed in aluminum almost entirely by Compton scattering and electron recoil. Therefore the absorption in aluminum is better suited to the calculation of wave-length and voltage than is an absorption in lead which has, in addition to the Compton process, a large photoelectric absorption of rapidly varying proportions that is less accurately known for this range. However, the linear absorption coefficient for lead does indicate a voltage close to that determined by absorption in aluminum.

For voltages determined from absorption coefficients, the logarithmic intensity-ratio curves for absorption in lead are found to agree with the slope of lead absorption curves obtained with other types of x-ray tubes that were operated with known voltages. From a calorimetric measurement of the kilowatts associated with an established voltage, the neighboring voltages are estimated from the change in the kilowatts in the coil.

An x-ray measurement of voltage is not needed when the voltage is used for the double acceleration of ions, for then the minimum voltage for which the ions traverse their path in synchronism with the alternating voltage is sharply defined.

Dimensions

The impedance varies as the square root of the scale of the dimensions to which the resonance transformer is built. Since the voltage varies only as the fourth root of the linear dimensions, the size of the transformer is chosen as small as the power requirements will permit, whereas the optimum geometric proportions are chosen by trial-and-error. It is difficult to obtain sufficient power below 40 meters wave-length, and furthermore, the coils of the third class of transformers cannot be adequately water-cooled if constructed for wave-lengths less than this.

It is interesting to note that one of the second class of transformers, a resonant $\frac{1}{4}\lambda$ line built for 40 meters would generate 5,000,000 volts with available oscillator tubes, compared to the 2,000,000 volts to which the coiled type of transformer could be forced, provided of course that a tube could withstand such voltages without field-current break-down. But the $\frac{1}{4}\lambda$ line would require an enormous vacuum tank 35 feet high and 15 feet in diameter, surrounding the two vertical parallel lines, Fig. 2(f). To obtain extremely low resistance each conductor of the line would be about 18″ in diameter, tapering somewhat at the high voltage end. This indicates that only the coiled third class of transformers are sufficiently compact for ordinary use.

Coil connections

Five types of resonance transformers of the third class are shown in Fig. 2 for $\frac{1}{4}\lambda$ coils; with four corresponding arrangements for $\frac{1}{2}\lambda$ coils. The types in Figs. 2(a–b–c) use three kinds of inductive primary coupling, whereas those in Figs. 2(d–e) have capacitive primary coupling. Push-pull oscillators are suited to all of the $\frac{1}{2}\lambda$ coils; but single oscillators, Fig. 1(b), are needed by all of the $\frac{1}{4}\lambda$ coils excepting the separate inductive primary of Fig. 2(c), which, like the half wave coils, will operate with either single or push-pull oscillators. In the special case of the $\frac{1}{4}\lambda$ coil with separated primary and push-pull oscillators, the load on the two tubes is more evenly balanced by providing a grounded electrostatic shield between the primary and secondary coils.

The capacitive analogue of the inductive primary of Fig. 2(c) is a voltage step-down device. However, to step the voltage down for transmission over a high-frequency transmission line, the transformer of either Figs. 2(b), or 2(c), working backwards is more practical.

The $\frac{1}{4}\lambda$ coils of Figs. 2(c) and 2(e) are simplest to construct and adjust. The latter is unique in that it may be connected directly to a single oscillator tube of unlimited size, because with a circuit corresponding to Fig. 1(b) it requires no blocking condenser. The oscillator circuit of greatest ease of adjustment and freedom from parasitic oscillations is that of Fig. 1(d), which combined with Fig. 2(c), is shown in the x-ray generator, Fig. 3, which has been used throughout most of the development.

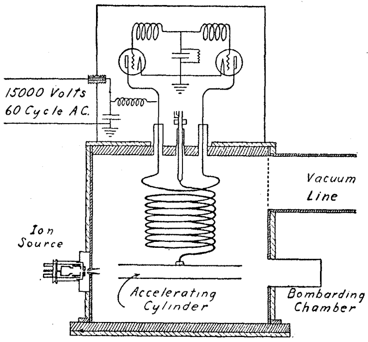

FIG. 4. System for the double-acceleration of protons, deutons or helium ions.

OSCILLATOR TUBES

A low-resistance coil inside of a copper-lined vacuum tank can form a resonance transformer whose total resonant impedance $R' = L/RC = 3$ megohms. This requires a little over 200 kilowatts to develop 800,000 volts across it. When, in addition, the coil must also support an ion-accelerator electrode, Fig. 4, the increased electrostatic capacity to the walls greatly increases the required high-frequency power, which may exceed 600 kilowatts for some accelerator systems. Higher voltages will require even more power, and this has led to the development of very large short-wave oscillator tubes, for driving the resonance transformer. The essential feature in the design of these tubes is a low inter-electrode capacity, such that the parasitic or natural frequency of the primary circuit of Fig. 3 is more than twice as high as the main resonance transformer frequency of 6000 kilocycles.

Three sizes of tubes, having continuous output ratings of 100 kw, 200 kw and 300 kw, have been constructed in the laboratory shop. The anode voltage supply is unrectified 15,000 volts r.m.s. 60 cycle a.c. This greatly reduces the heat associated with a given maximum of generated voltage, and increases the maximum to which the output power can be modulated. Thus by running the filaments exceedingly hot, a push-pull pair of these 300 kw tubes can probably deliver 1000 kw at 6000 kilocyles during the maximum of the 60 cycle voltage, although this output has not yet been required for ion acceleration.

The power dissipated in the load, averaged over a complete cycle, is much smaller than $\frac{1}{4}$ of the maximum, because of the distortion by the non-linear modulation of the output wave-shape. In the x-ray coil, for example, when generating 800,000 volts, the groups of radiofrequency oscillations reaching a peak of 200 kw have an average heating effect equal to a continuous dissipation of only 30 kw in the resistance of the coil, away from which the heat is carried by the cooling-water.

Oscillator tube construction

The six-inch diameter copper anode of each 300 kw oscillator tube is cooled by a swiftly moving sheet of turbulent water only 0.025″ thick, inside of the waterjacket, which with its expansion joint is soldered around the anode. The tube undergoes no heated bake-out because it is continuously exhausted. Therefore the small clearance between the anode and the brass waterjacket can be accurately maintained. Ordinary solder is used, and because of the poisonous action of water-vapor upon the emission from tungsten filaments, the joints of the waterjacket are distinctly isolated from the soldered joints in the wall of the vacuum-tight envelope.

The cylindrical grid structure consists of a helix of copper wire wound around a frame of six water-cooled copper pipes, to which these wires are soldered. The grid is soon coated with evaporated tungsten which keeps the secondary emission reasonably low. Within the grid are placed 12 filaments of 0.050″ tungsten 14 inches long. Each filament has individual spring tension, and is so easily replaceable that the unusually high temperature of 2700°K is practical, giving a total emission of 200 amperes from the filaments of each tube.

The three electrodes are insulated by two glass cylinders which form part of the vacuum wall, and which are sealed to the metal parts by red sealing wax. Each seal is protected from electric fields and radiant heat by metal shields on the inner side of the glass.

Each tube is continuously exhausted to 10^{-5} mm Hg pressure by an Apiezon oil diffusion pump system whose over-all speed is 100 liters per second.

The oscillators are mounted on waxed maple boards inside of a large copper house, with by-pass condensers connected to all the power leads to completely prevent the escape of current which might radiate, thus eliminating any interference with radio communication.

POWER SUPPLY

Advantages of alternating current

The chief advantage of alternating current for the anode power-supply, aside from avoiding costly rectifiers, is the great ratio between the peak and the average high-frequency power output. But another almost priceless virtue of an alternating power supply is the alternate idle half-cycles which permit de-ionization of arcs that occasionally occur in the high-voltage circuit. Discharges from the high-voltage coil are harmless, because they either kill the high-voltage oscillations and cease, or else develop a parasitic oscillation and low-voltage arc, which dies out at the end of the half-cycle. Adequate de-ionization time, provided by the idle half-cycle, combined with a very fast vacuum pumping-system, prevent such momentary discharges from interrupting operation for more than one or two cycles. Far from being damaged, the all metal surfaces in the high-voltage chamber are merely cleaned by the discharge, so that even higher voltages can be used.

When the oscillator filament heating-current is shifted 90° out of phase with the alternating anode supply-voltage the emission current heats all parts of the filament evenly, just as with a center-tapped a.c. filament and d.c. anode voltage.

Methods for voltage variation

A motor-generator to operate the anode voltage-supply transformer provides the best means of varying the generated high voltage. A 150 kva transformer will supply power for a pair of 100 kw tubes driving a 800,000 volt x-ray generator in continuous operation. A transformer operated from a fixed-voltage power supply involves the simplest equipment for varying the high voltage if the transformer is connected to the anode circuit through a flowing water-column variable resistance. This resistance can use the cooling water discharged from the oscillators. A variable reactance in the power-line seriously lowers the power-factor which is already low because of the half-cycle load.

A reduction of the step-up ratio is an efficient means of lowering the high voltage for outgassing the surfaces of the resonance transformer and vacuum tank while conditioning them for operation. This is done by increasing the impedance of the part of the circuit into which the tubes deliver their power. Three good methods are available for thus decreasing the generated power. The simplest is one in which the primary of Fig. 3, for example, if mounted on sylphon supports, can be moved nearer to the main coil while outgassing. The other two systems for reducing the step-up ratio involve an intermediate transmission line.

In the circuit of Fig. 1(e), the impedances of the transmission line and of the primary and secondary of the high-voltage resonance transformer, No. 1, have permanently fixed ratios; but the impedance ratio of the auxiliary resonance transformer, No. 2, between the oscillator tubes and the line, can be varied to change the power output by providing this transformer with a tapped secondary to connect with the line. In addition to these two transformers and interconnecting line of the second method, the third method includes still another resonance transformer, No. 3, of variable ratio, inserted between the line and its connection to the secondary of the transformer that couples the line to the tubes, Fig. 1(e). This third resonance transformer is simply an impedance-matching "π" network common to transmission line practice. These two methods involving the line permit a convenient location of the oscillator at a distance from the tank, and step-up ratio-changing incurs no danger of springing leaks in the main vacuum-tank.

All three of these methods of lowering the step-up ratio permit abnormally high voltages to develop at the oscillator tubes, which may limit the extent of the reduction of the main high voltage, unless the oscillator power-supply voltage is also reduced.

Transient voltages

The presence of the direct anode voltage in the high-voltage vacuum-tank during a high voltage discharge may momentarily short circuit the anode voltage-supply. A peculiar property of rarefied gaseous discharges is their ability to suddenly cease conducting, which could cause the momentarily short-circuited power-supply transformer to become cleared so abruptly that it would develop a tremendous surge voltage. A $\frac{1}{4}$ mfd. condenser across the supply line prevents the surge from rising to destructively high values. But now about 50 ohms is needed between this condenser and the anodes to prevent flashes in oscillator tubes, as well as flashes from the primary in the tank, from liberating sufficient gas to disrupt operation.

The transmission line, on the other hand, with a well-insulated inductively coupled resonance transformer between the oscillator and the line, Fig. 1(e), avoids the high voltage surges by not having the anode voltage enter the high-voltage tank. Hence with this system there is no need for the surge-absorbing condenser which increased the severity of the flashovers.

GRID BIAS

Considerable variation in the high voltage that is generated with a fixed anode voltage can be effected by adjusting the grid-bias voltage. In fact, the reducing of an excessive bias is the most convenient means of advancing the voltage as the tank is progressively outgassed.

The grid-bias voltage is most easily obtained from a grid-leak and condenser. Since the grid-leak dissipates several kilowatts, the most satisfactory resistance is that of a flowing water-column of variable length, between graphite electrodes. When the alternating anode supply-voltage is below the operating range, the tube impedance is so great that oscillations cannot occur, and considerable power is wasted in non-oscillatory anode current. This can be minimized by maintaining a constant bias instead of the variable voltage of the grid-leak.

Rather than use a motor-generator, an effectively constant bias can be supplied during the alternate half-cycles of operation by square-wave pulses from a unique rectifier. An ordinary rectifier cannot pass the grid current because this current flows in opposition to the bias voltage. But if a large hot-cathode mercury-vapor rectifier is connected in series with a resistance across 110 volts a.c., the voltage drop across the tube during one half-cycle never rises, for example, above 15 volts. A large 110–11,000 volt transformer connected across this tube will give practically constant 1500 volts for nearly a half-cycle, with the striking property that grid current can flow *against* this voltage, and merely increase the current in the rectifier tube. The grid potential cannot become highly positive during the next half-cycle because the resistance which connects the primary to the 110 volt line limits the power which a positive grid can draw from the transformer.

To initiate oscillations, the biased oscillators must have their grids made more positive by a transient voltage which may be applied as the anode voltage nears its maximum. As few cycles of operation as are desired may be used each second. The efficiency, as an x-ray generator, is greatly increased by quadrupling the electron emission and using only every fourth cycle of the power source, with a corresponding reduction of the resonance transformer power dissipation.

COIL CONSTRUCTION

The coil is located in a water-cooled copper-lined steel tank more than a meter in diameter and equally high, which is exhausted to less than 10^{-5} mm Hg pressure by a 250 liter-per-second Apiezon oil diffusion pump system. The shape of the coil is chosen to give the maximum value of the ratio L/RC consistent with adequate cooling. A typical high-voltage $\frac{1}{4}\lambda$ coil has 12 turns of $\frac{7}{8}''$ diameter copper pipe wound into a cylindrical coil about 14 inches in diameter and 15 inches long. It is supported by one end which is grounded where it passes through the roof of the surrounding metal tank to connect with the cooling-water system. The resonant frequency is about 6000 kc or 50 meters wave-length.

The coil is wound of two concentric copper pipes, so that cooling water may flow down between their walls and return in the inner pipe, and also cool whatever electrode is attached to the high-voltage end of the coil. Although a peak of over 200 kw is produced in the coil by the modulated high-frequency currents when developing 800,000 volt x-rays, the average rate of heating equals a continuous dissipation of only 30 kw, which the cooling water must carry out of this coil, in addition to the heat developed in the high-voltage electrode. Heat-transfer between the outgoing and the incoming water is reduced by covering the inner pipe with rubber tape. To protect the rubber against erosion, it is wrapped with a layer of copper tape.

For x-ray use, either the anode or the cathode may be on the high-voltage end of the coil. In the latter case the filament leads may be placed inside of one of the water passages in the pipes of which the coil is wound.

Since it has twice the impedance of a $\frac{1}{4}\lambda$ coil, a $\frac{1}{2}\lambda$ coil will generate $\sqrt{2}$ times as much voltage as will the $\frac{1}{4}\lambda$ coil, for a given power. Hence an x-ray generator superior to the $\frac{1}{4}\lambda$ coil of Fig. 3 may be obtained by using one of the $\frac{1}{2}\lambda$ coils of Fig. 2, connected as in Fig. 1(d), having an anode on one end and a cathode on the other.

A smaller $\frac{1}{4}\lambda$ coil, for twice as high frequency, is obtained if instead of using concentric pipes, a single small pipe is wound into a coil that has its cooling water discharge out of its high-voltage end into the equally high-voltage end of a similar coil, and thus return to ground. These two coils with a single voltage maximum may be located on a common axis with their high-voltage ends adjacent, in which case a reversed direction of winding of one coil improves the magnetic circuit. The simplest transformer to adjust, however, is the large $\frac{1}{4}\lambda$ coil wound with concentric cooling pipes.

X-Ray Generator

The x-ray cathode structure shown in Fig. 3 has a straight tungsten filament surrounded by a grid that has a negative bias of several thousand volts. The purpose of the grid is to prevent the escape of electrons, except when the nearby anode is near its positive voltage maximum. An emission current of 5 milliamperes, average-value, may actually consist of short pulses of current which momentarily rise to 200 milliamperes. Because of these high current densities, it is not practical to use a zero potential grid and thereby obtain a similar bias action by means of space charge alone. The ideal cathode is a very hot one whose emission is controlled solely by the grid. Since the anode potential must be near its most positive value in order that an electron current may flow to it, the x-rays are produced almost as though the anode were connected to a high-voltage direct-current supply.

The intensity of the x-rays is as great as the intensity produced by other types of high-voltage tubes. It is limited only by the overheating of the water-cooled target. Special mechanical damping of the coil is necessary to prevent the coil that supports a positive ion accelerator electrode from vibrating, but for x-rays, it is advantageous to use no damping.

The free end of the coil may be kept in sustained vibration by the magnetic and electric forces on the coil, with the amplitude of vibration controlled by the adjustment of the grid tuning coil. This movement of the high-voltage coil changes its frequency relative to the grid tuning, and the changing efficiency of oscillation alters the power output and the forces on the coil. The magnetic field is sufficient to unwind the coil through an angle of 3° in the steady vibrationless state. The motion of the x-ray target is largely at right angles to the direction of the electron stream, hence the small area of impact remains at rest in space while sweeping over a large anode surface to facilitate the heat dissipation. Without this movement of the anode, the stream of electrons can be swept over the target face by deflecting fields analogous to those of cathode-ray oscillographs.

The absorption curves of Fig. 5 indicate an operating voltage of 800,000 volts with 30 kw in the coil. The voltage is confirmed by the absorption coefficient per electron in aluminum, using the Klein-Nishina formula. These curves were obtained from a resonance transformer driven by a pair of 100 kw oscillator tubes, connected as in Fig. 3. With a filter of 5 mm steel and 5 mm lead, the intensity at 0.7 meter from the tungsten target, when using 2.8 milliamperes emission, is 20 Roentgen units per minute. As it is normally adjusted, this resonance transformer will carry an electron current of 10 milliamperes to its high-voltage end without noticeably lowering the voltage, but no target can withstand it. By virtue of the resonant circuit, the sinusoidal voltage of the useful and inverse half-cycles are equal.

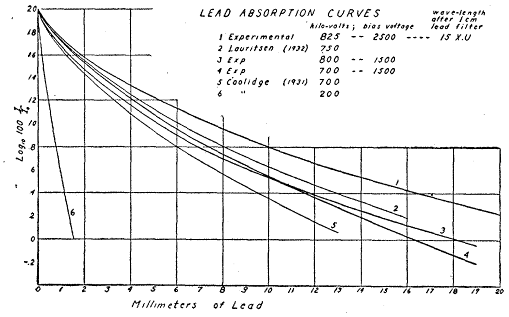

FIG. 5. Absorption of x-rays in lead.

The 700 kv and 800 kv curves were taken with the x-ray cathode-grid bias-voltage somewhat lower than the value subsequently adopted. The effect of the higher bias is clearly seen in the 825 kv curve, which lies much higher than the others, indicating a greater freedom from soft x-rays. Some earlier curves of Coolidge[2] and Lauritsen[3] are shown for comparison.

For therapeutic use, the entire tank is covered with 2″ of lead, except at the treatment portholes, and is placed in a room walled with $\frac{1}{4}$″ lead with an additional 2″ of lead between the tube and the operator.

With increased water-cooling of the high-voltage circuit, the voltage can be raised whenever clinical observations justify the change.

POSITIVE ION ACCELERATOR

The original purpose in developing the high-voltage resonance transformer was for the multiple acceleration of ions. The most intense source of ions of gaseous elements has proved to be that type which was originated to supply mercury ions for multiple acceleration.[4] The plasma of a low-voltage high-current gaseous discharge of the hot-cathode type supplies the ions which are accelerated and focussed by the field in a positive-ion space-charge sheath of 20,000 volts or more, which the ions cross in falling toward a negative electrode that is pierced by a small hole through which emerges the ion beam of several milliamperes.

The scheme for the high-voltage double-acceleration of hydrogen or helium ions consists in having a hollow open-ended horizontal water-cooled metal cylinder attached to the high voltage end of the coil, Fig. 4. When this cylinder is highly negative, the intense beam of many milliamperes of positive ions is accelerated into one end of it from the ground-potential ion-source. These ions travel along the axis of the hollow field-free interior and emerge from the opposite end of the accelerating cylinder one half-cycle later when it is highly positive. The ions then receive a second acceleration, doubling their energy, as they pass to the wall of the tank, through which they emerge to be used at ground potential, for bombarding atomic nuclei under investigation.

The development of a high-voltage double-acceleration tube for protons and deutons has just been completed by Dr. J. J. Livingood and the writer, and is soon to be described in detail. Likewise, a description of a resonance transformer x-ray tube installed at the University of California Medical School by Dr. M. S. Livingston and M. A. Chaffee will soon be published.

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[2] Coolidge, Dempster and Tanis, Am. J. Roentgenol. and Rad. Therapy **27**, 405 (1932).

[3] Lauritsen, private communication.

[4] D. H. Sloan and E. O. Lawrence, Phys. Rev. **38**, 2021 (1931).