DEVELOPMENT OF TRANSMITTERS FOR FREQUENCIES ABOVE 300 MEGACYCYLES*

By

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Summary—*The fundamental functions of the electrons and their work cycle, in the interelectrode space of high vacuum tubes, are discussed. It is shown how the triode feed-back circuit becomes inoperable at very high frequencies due to space-time and reactance characteristics. It is further shown how the space-time conditions can be organized to benefit the maintenance of oscillation instead of becoming a detriment. Some of the more familiar arrangements, such as the Barkhausen and the magnetron circuits, which are based on this principle, are discussed in some detail. With these illustrations as a background the author describes a new method of frequency multiplication at very high frequencies. This method yields much greater power outputs than hitherto possible and promises to become very useful.*

Various means for frequency stabilization are referred to and the merits of frequency controlling devices, such as crystals and low power factor circuits, are compared.

Special problems encountered in the application of modulation at very high frequencies are described and reference is made to methods developed to meet these problems.

Practical considerations of circuit arrangements are described in some detail. Several examples of transmitter design are given. These sections are illustrated with photographs.

Important points in connection with antennas and transmission lines are discussed and the results of some measurements are given.

The paper ends with a brief reference to some propagation results obtained by RCA Communications engineers and others.

Introduction

THE purpose of this paper is to report progress in theoretical conception as well as in practice pertaining to the application of the frequency band between 300 and 1000 megacycles to radio communication.

The Electron Performance in High Vacuum

Since electrons are negative electric charges, their presence in the interelectrode space of a vacuum tube causes, by virtue of electrostatic induction, positive charges to be distributed over the electrodes which

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will vary in accordance with variation in position of the electrons. If the external circuit consists of a resistance it can be seen that the current produced in this resistance, by virtue of the electron motion in the interelectrode space, always causes a voltage drop on the electrodes which retards the electron motion and decreases the rate at which electrons enter the interelectrode space.

When the electrons land on the electrodes, the positive charges in the electrode meet the corresponding electron charges and are cancelled.

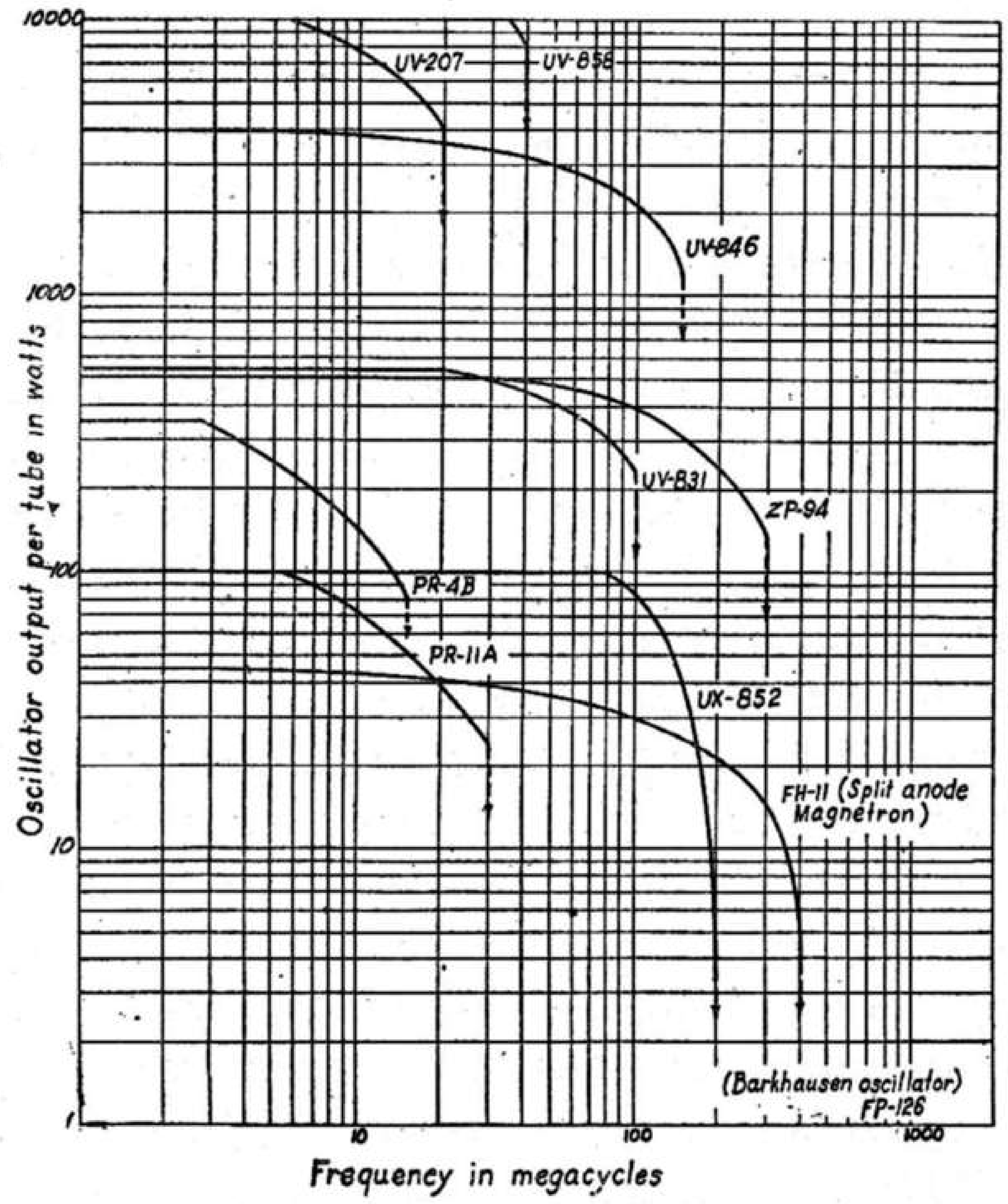

Fig. 1—Frequency versus power output at rated anode dissipation of some American transmitting tubes. Curves not otherwise indicated refer to performance in triode feed-back oscillators. These curves were originally published by W. C. White in the *General Electric Review*, September, (1933).

The current caused by the electron motion therefore ceases at the moment the electrons land. Whatever kinetic energy the electron possesses at the time it lands is lost in the form of heat.

The Electron Performance in High Vacuum at High Frequencies

When the well-known, triode feed-back oscillator is adjusted for higher and higher frequencies, a frequency will eventually be reached beyond which the device fails to perform. (Figure 1.) It is usually assumed that the increased circulating currents necessary to maintain proper electrode potential across the decreasing capacitive reactance of the interelectrode space cause prohibitive losses. This is, however, not the major factor in well-designed circuits and the chief limitations are instead to be found in the vacuum tube itself.

Hitherto it has been possible to neglect the interelectrode transit time of the electrons in vacuum tube phenomena. The finite velocities of the electrons introduce phase lags in the electron motion which are unsuitable to the triode feed-back method and results in a reduction of efficiency. Accompanying this phase lag electrons are trapped in the interelectrode space. As the transit period terminates, the electrons in the grid-cathode space come to a stop. The grid potential is rapidly becoming very negative and assumes a controlling effect upon the field in the grid-cathode space. This field therefore changes direction and the electrons in the grid-cathode space are thrown back into the cathode at high velocity, resulting in high kinetic loss. Since the plate becomes more positive, while the grid grows negative, the field in the grid-anode space is increased. The electrons in this space therefore receive additional impetus in the direction of the anode and arrive there at high velocity and thus with a high kinetic loss. At the lower frequencies the interelectrode spaces are "cleaned out" before the potentials have had time to reach excessive values. The higher the frequency the greater becomes the number of electrons which fail to accomplish the transfer or which transfer under field conditions which cause excessive kinetic losses. The existence of these losses has previously been referred to but not explained.[1] Since a great portion of the grid input energy, due to trapped electrons, appears at the cathode, its value can be observed by noticing the increase in cathode resistance from the increased cathode temperature. Estimates of the loss obtained in this way indicate that it is a major source of frequency limitation in conventional transmitting tubes.

In order to reduce the losses during the "cleaning-out" period, the interelectrode space must be made small in volume so that it contains a small number of electrons in transit. If the power output is to be reasonably retained and since the cathode emission at the present cannot be increased, the cross section of the interelectrode space cannot be excessively reduced. The only way to obtain substantial decrease of volume is thus to reduce the length of the interelectrode space. While this on one hand results in increased capacity with the handicap of higher circulating currents it improves the phase relation between the moving electrons and the electrode potentials. Thompson and Rose[2]

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[1] F. B. Llewellyn, "Vacuum Tube Electronics at Ultra-High Frequencies," *Proc. I.R.E.*, Vol. 21, pp. 1532-1574; November, (1933).

[2] B. J. Thompson and G. M. Rose, Jr., "Vacuum Tubes of Small Dimensions For Use at Extremely High Frequencies," *Proc. I.R.E.*, Vol. 21, pp. 1707-1722; December, (1933). (See Page 334.)

have had rather outstanding success in compromising these factors in the design of receiving tubes for very high frequencies.

Generation of Higher Frequencies

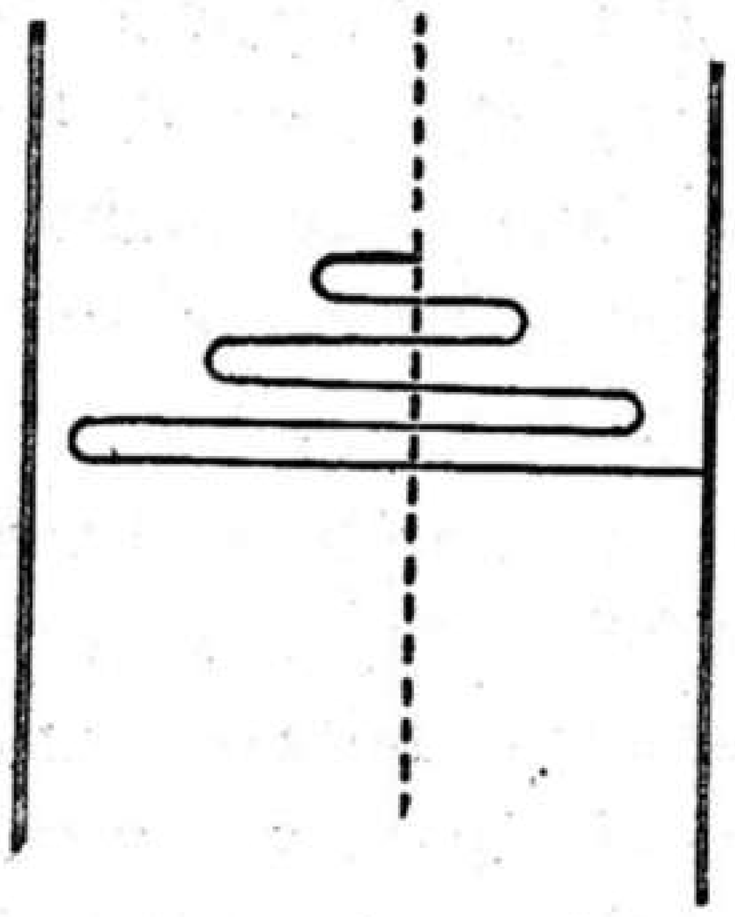
In the triode feed-back circuit the electron flow takes place during a very short favorable portion of the oscillation cycle. Due to the finite velocity of the electrons it has been shown that it is not possible to confine the existence of electrons in the interelectrode space to such short portions when the frequency is increased. As a result, and because of the nature of the circuit, the oscillating power created in the external circuit is returned to the electrons and lost in the form of heat. It is, therefore, necessary to choose methods in which the electrons may perform usefully during more prolonged portions of the oscillation cycle; in which the time of travel of the electrons and the electric fields produced by the electrons themselves contribute to the condition of oscillation. In other words, the electrons themselves and their motions constitute the whole oscillator. All such oscillators require electric, and often also magnetic, field conditions such that the electrons as a group are subjected to unstable conditions which can produce whistle effects in the interelectrode space. The periodic pressure effects in an air whistle would thus correspond to the potential effects set up by the periodic formation of concentrations in space charge.

These conditions may be obtained if the electrons are given an opportunity to miss an anode as they are accelerated toward it. After missing the anode and as the electrons are thus carried away from it by their own momentum, they will be subject to a retarding force instead of an accelerating force from the anode. They will eventually come to a stop and again be accelerated toward the anode. The positive direct-current potential on the anode thus makes the electrons describe a pendulum motion. Since there are many electrons and thus many such pendulums they cannot be permitted to oscillate at random phase since they will then cancel each other's effect upon the external circuit. The pendulum motions must, therefore, be organized to operate in unison. By comparison with the traffic congestion on a highway which occurs at points where the traffic speed is reduced, it is easily seen that congestion of electrons will arise in the regions of the interelectrode space where the electrons turn around. As these accumulations form, the resultant electric field in the interelectrode space is gradually being altered. This alteration influences the motion of the electrons. Also, electrons arriving later at the turning region, retard the turning around of the earlier ones, while, on the other hand, the earlier electrons speed up the turning around of the later ones. This condition is therefore conductive to synchronization of the oscillating electrons so that they form into groups. When the oscillating electrons form into groups they will thus no longer cancel each other's influence upon the external circuit. The losses from the currents induced in the external circuit by the group motion will, therefore, introduce a load upon this motion, and the motion of the individual members of the oscillating electron group will become attenuated. This attenuation takes place in the direction toward the prime mover, the anode, where the electrons are ulimately deposited. Since they are continually being replaced by newly emitted electrons of high momentum, the motion of the group as a whole is not attenuated but may be represented by an average of the motion of its continually changing members. It should also be clear that many of the electrons will be subject to accidents so that they will prematurely collide with the anode. There is no electrode system known where this can be prevented. The fact should, however, be noted that while such collisions represent very great losses the kinetic energy so spent is not taken from the oscillating energy in the external circuit as the case happened to be at the end of transit in the triode feed-back oscillator. Practically all of the momentum possessed by the electrons has been derived from acceleration by the interelectrode, direct-current field. Since the cathode is inherently located in a region where the electrons reverse their motion and since the space charges, there forming, appear periodically, it is clear that the emission from the cathode will also be subject to periodic fluctuations. This phenomenon and the synchronizing tendency between the individual electron pendulums as they approach the turning regions amplify one another and establish a reasonably substantial tendency for the electrons to form a whistle effect in the interelectrode space.

The best known methods utilizing these principles are the Barkhausen and the magnetron methods. In both these arrangements the electrons are made to turn around before reaching the plate. In the Barkhausen method an ordinary three-element vacuum tube may be used. The grid is highly positive and acts alternately as accelerator and decelerator for the electrons which pass through. The plate is mostly operated at a slightly negative potential to facilitate the reversing of the electron motion before the electrons reach the plate. The path of an individual electron is shown in Figure 2.

The magnetron, as is well known, consists in its most common form of a centrally located cathode which constitutes the axis of a cylindrical anode. The anode has a high positive potential and the electrons are made to miss it by virtue of the deflecting properties of an axial magnetic field. The path of an individual electron is shown in Figure 3.

One very interesting phenomena in common for both the Barkhausen and the magnetron methods is the difference in the behavior of the oscillations when the tuning of the external circuit is approached from a state of lower or higher circuit tuning. This phenomenon is due to the fact that the voltage inducing effect from the electrons is twofold. The electrons accumulating near the plate or near the cathode cause field variations similar to such as would be produced by variations in electrode potential. The voltage drop across the resistive component of the external circuit is, however, a maximum when the electrons are in a state of highest velocity. This voltage is therefore



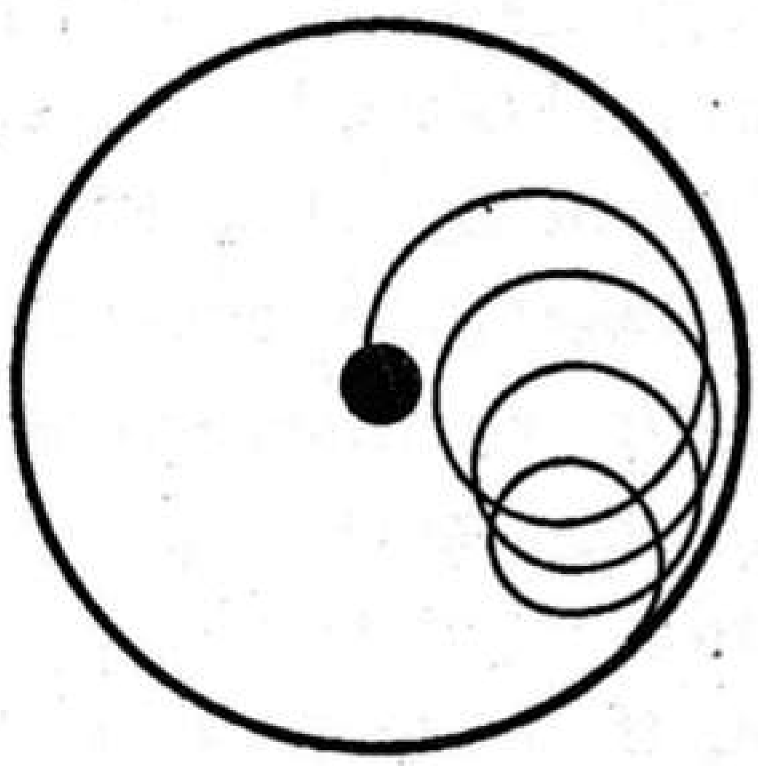


Fig. 2—Attenuated path of the individual electron when partaking in organized group motion in a triode pendulum oscillator.

Fig. 3—Attenuated orbit of the individual electron when partaking in organized group motion in a magnetron oscillator.

ninety degrees in phase lead of the voltage set up by the electron accumulations. The combined voltage on the electrodes therefore tends to make the electrons turn around sooner. The frequency is increased. Since the frequency of oscillation thus increases as the resistance between the electrodes is increased, a peculiar effect occurs when the tuning of the interelectrode circuit is varied. If the circuit resonance is made to approach the electron oscillation frequency from a lower value, the electron oscillation in the tube will recede upward and will thus have to be trailed by the circuit tuning. If the circuit tuning is adjusted above the electron oscillation frequency and then lowered, the oscillation frequency moves up to meet it. In the Barkhausen case this phenomenon has been called Gill and Morell oscillations.

Effects in the Vicinity of Electrodes

In addition to the effects of the electron motion so far considered it may also be of interest to consider the local effects in the close vicinity of an electrode.

The electric field from the electron, which at a distance covers the electrode fairly uniformly and causes a current of no definite origin to flow through the electrode, as the electron moves, becomes more concentrated as the electron nears the electrode. The current origin in the electrode becomes more and more defined into a spot under the electron where it becomes very concentrated. The direction of this current is toward the spot if the electron is in an approaching state and away from the spot if the electron is in a receding state. These considerations, of course, do not apply to electrons moving parallel with the electrode surface. This phenomenon is naturally extremely rapid in that such concentrations do not become noteworthy until the electron is fairly near the electrode. It takes place during a very small fraction of the total transit time of the electron. Its period is therefore greatly in excess of that represented by the transit time and represents real ultra-high frequencies. These "surface oscillations" are independent of the frequency at which the device operates and depend only on number and velocity of the electrons.

Carrying the discussion a little further it becomes increasingly difficult to see where to draw a line between these "spot impulses" and heat quanta. It depends largely upon the size of the area under consideration if the period belongs to the radio-frequency region or the heat region. If the electron is headed for a landing on the electrode the spot becomes smaller and smaller until we reach the molecular and atomic structure of the electrode where the remaining kinetic energy is interchanged.

If the electron does not approach the electrode quite so close, like for instance when an electron passes through a grid structure the frequency produced, while high, is definitely one far below that of heat.

Not being organized these impulses cannot be shown in the external circuit under ordinary conditions. It may, however, be possible, by special methods to set up conditions, by using a very restricted number of electrons, whereby these oscillations may be shown.

Negative Resistance

The expression "negative resistance" is very commonly used in explaining oscillatory phenomena. Reference to it in the previous discussion has been avoided until sufficient background could be established for a clear understanding of its nature. It has been seen how in the triode feed-back circuit maximum electron transit is obtained when the anode potential is at a minimum. As the anode voltage decreases the current through the tube increases. In an electron pendulum device the electrode toward which electrons are moving has its highest negative tendency as the electrons possess their greatest radial velocity. Therefore, as the current through the tube increases the electrode voltage decreases. In the so-called dynatron method, similar current-voltage conditions are obtained with the aid of secondary emission. The electrons are usually made to pass through a grid of high positive potential toward a plate of less positive potential. The electrons will, therefore, land on the plate with considerable velocity, causing other electrons in the plate to bounce off and be attracted by the grid. As the positive potential on the plate is increased the oncoming electrons will have a higher velocity and thus cause more electrons to bounce off and travel in the opposite direction. The total current will decrease because the ratio between electrons coming to the plate and leaving it has been decreased. All these methods, therefore, have the one characteristic in common that current and voltage vary inversely. This is characteristic of negative resistance. Since the operation of the dynatron is not based on time delay in electron transit this method, in its fundamental principle, is not adaptable to generators of extremely high frequencies. More or less developed dynatron action is, however, often obtained in conjunction with other methods whenever electrodes are bombarded by high velocity electrons.

Frequency Multipliers

Since the electron pendulum methods are critical to fields and space charges, each type of tube has a fairly well established maximum output at a particular frequency. The outputs from conventional sizes of tubes are limited to a very small portion of the power output of which they are capable when operating at frequencies where the time of electron transit is of no significance. It was, therefore, considered that if the frequency of the greater amounts of power possible to produce at the lower frequencies could be multiplied efficiently, greater power may also be realized at the higher frequencies.

The commonly known vacuum tube frequency multipliers, which are widely used for various purposes, consist of a triode, a circuit connected to the grid which is tuned to the fundamental frequency and a circuit connected to the plate which is tuned to a harmonic frequency. The grid has a negative bias and the plate has a positive potential. The frequencies used are usually well below the values at which the time of electron transit assumes significance. This shortness of the transit time is in fact an asset since the production of harmonics depends on the immediate establishment and discontinuation of electron current as the grid potential passes above and below the cut-off value. By virtue of the plate power the device also operates as an amplifier.

As the input frequency is increased, the electrons will remain in the process of transit while the electrode potentials may vary considerably. Like in the triode feed-back circuit this is very detrimental. As the grid potential goes below cut-off value, it first retards the electrons moving toward it from the cathode. The electrons therefore deliver the energy they chiefly received from the direct-current source into the external oscillating circuit and the grid receives an impetus in accord with its negative swing. As the grid continues to become more negative the electrons will finally come to a standstill whereafter they will be accelerated back toward the cathode. They will then draw power from the external circuit. The acceleration received in this direction is greater since the grid is now very negative. The total effect of the motion from the cathode and back again is, therefore, a loss. The electrons in the grid-anode space received added acceleration in their original direction as the anode potential swings in a more positive direction. This accelerating power is thus also obtained from the oscillating energy in the external circuit. Both the fundamental frequency circuit and the harmonic circuit, therefore, lose more and more of their power as the frequency is increased.

Due to the increase in potential gradient toward the central cathode in cylindrical element tubes the greatest effects upon the motion of the electrons are, of course, obtained in this region. Electrons which emerge from this region have a more predetermined motion for the rest of their path than electrons in flat element tubes. This condition makes the electrons passing through the interelectrode space of cylindrical tubes less sensitive to variation in electrode potentials, during a great portion of their journey, than in flat electrode tubes with uniform fields. This fact, of course, holds regardless of the methods of oscillation employed.

At the lower frequencies the grid simply acts as a throttle which lets electrons through to the anode during a short portion of the cycle. The electron accelerating power required for the production of this motion and the subsequent harmonic it induces is thus chiefly taken from the direct-current plate supply. As the frequency is increased the number of electrons which do not complete their transit from cathode to anode becomes a greater and greater portion of the total number of electrons which enter the interelectrode space. The power stored in these electrons, as they are pushed toward the electrodes, is taken from the alternating-current component of the external circuit. It is, therefore, clear that as the frequency is increased, the frequency multiplier becomes less of an amplifier. The fundamental frequency input, instead of being only a guide to the electron performance, becomes a driving force. Since the frequency multiplier outputs at higher frequencies must derive the driving power from the fundamental frequency input it was necessary to find a way by which the motion of the electrons, thus driven, could be organized to converge, so that they would, during a certain phase of their motion, fall through an appreciable portion of the interelectrode space in the short time corresponding to a harmonic current. It was found possible to accomplish this by introducing a magnetic field which is perpendicular to the electric field. In a cylindrical tube this then becomes an axial magnetic field. The effect of the magnetic field may be most easily understood by referring to the curves in Figures 4, 5, and 6. For the sake of simplicity a tube with two

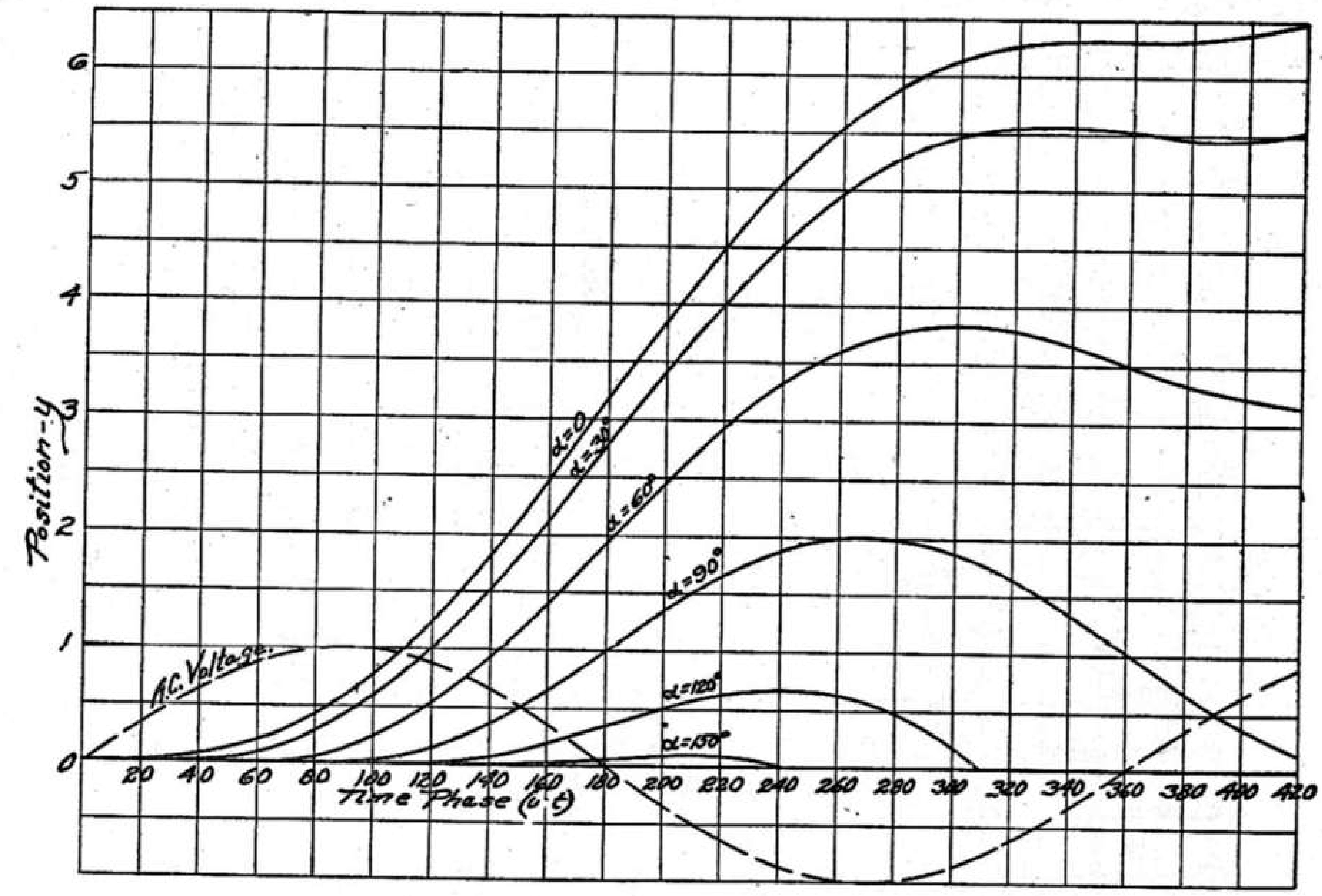


Fig. 4—Position versus time of electrons in an alternating-current field between flat electrodes. Each curve represents electrons which have left the cathode during a certain phase of the alternating-current cycle.

parallel plane electrodes is being considered. Alternating voltage is applied of such frequency that the time of transit is too slow for crossing the interelectrode space. The positions of the electrons leaving the cathode at different times, under the influence of the positive half cycle of the voltage on the other electrode, will be distributed throughout the space as shown in Figure 4. From these curves it can be seen that there is a tendency for the electron positions to become more and more divergent with time. Even a rectifying action can be observed in the motion of the electrons which leave the cathode during the first half of the positive half cycle. If a magnetic field, perpendicular to the electric field, is introduced it can be given such a strength that the electrons which leave the cathode successively, during the generous time period of a half cycle of the fundamental frequency, will all complete their return journey to the cathode within a very definite time limit. (See Figure 5.) By integrating the velocities, the curve shown in Figure 6 is obtained. It represents the shape of the resulting electron current curve. A transformation of the fundamental frequency power directly into a harmonic component thus becomes possible. The electron stream exhibits a positive resistance to the fundamental frequency current and a negative resistance to the harmonic. As the electrons return to the cathode they still possess considerable kinetic energy. If it is attempted to lower this kinetic energy by further

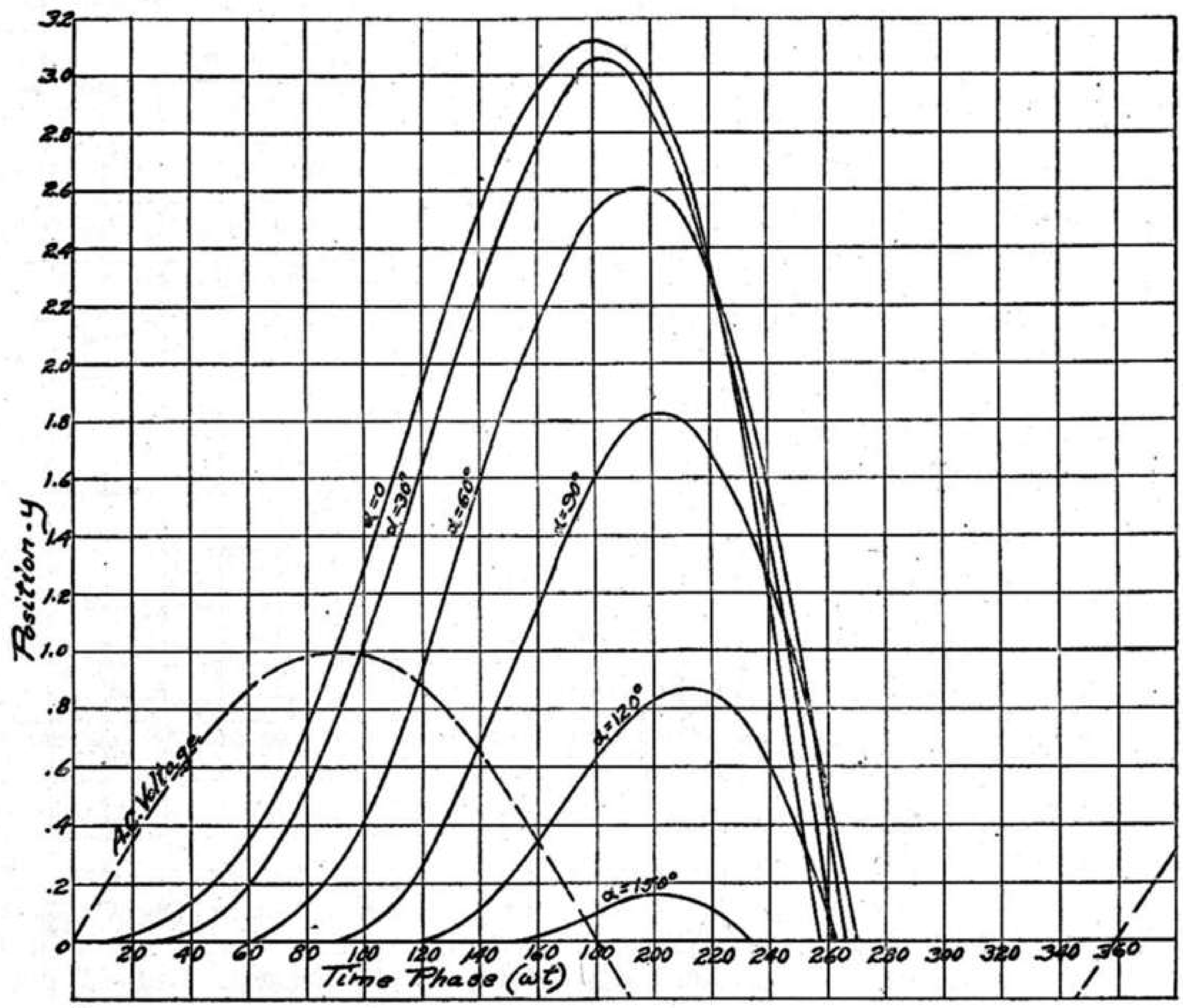


Fig. 5—Organization of positions shown in Fig. 4 when introducing a steady, transverse magnetic field. Note how the electrons, returning to the cathode, converge in respect to time.

circuit loading, the disorganizing effect from the load prevents further gain in efficiency. The efficiency also depends largly upon which harmonic is chosen. While the efficiency obtained when producing the second harmonic is high, the efficiency of the generator of the fundamental frequency oscillations is low since it has to operate nearer the border limits of the triode feed-back circuit than when a higher harmonic ratio is used. The multiplier efficiency, however, drops very rapidly as the harmonic ratio is increased. Fewer electrons become subject to complete organization. When odd harmonics are produced, two tubes can be operated in push-pull fashion. Very simple circuit arrangements are then obtained. From these considerations, the third harmonic has often been chosen as the most satisfactory compromise.

Among the standard tubes available, some three-element tubes happened to be the most satisfactory for frequency multiplication. Examples of such tubes are shown in Figure 7. Although it has been found most efficient to let all the elements become part of the circuit either for bias purposes alone, or for tuning purposes as well, the cathode and the grid are, of course, the essential elements between which the major electron performance takes place. The grid is negatively biased and the plate is given zero or negative potential. The input and the output circuits can be applied to any one of the elements as long as the combined circuit tuning produces potentials in coordination with the desired electron motion. Different values of magnetic field strength are sometimes necessary when choosing various modes of connection.

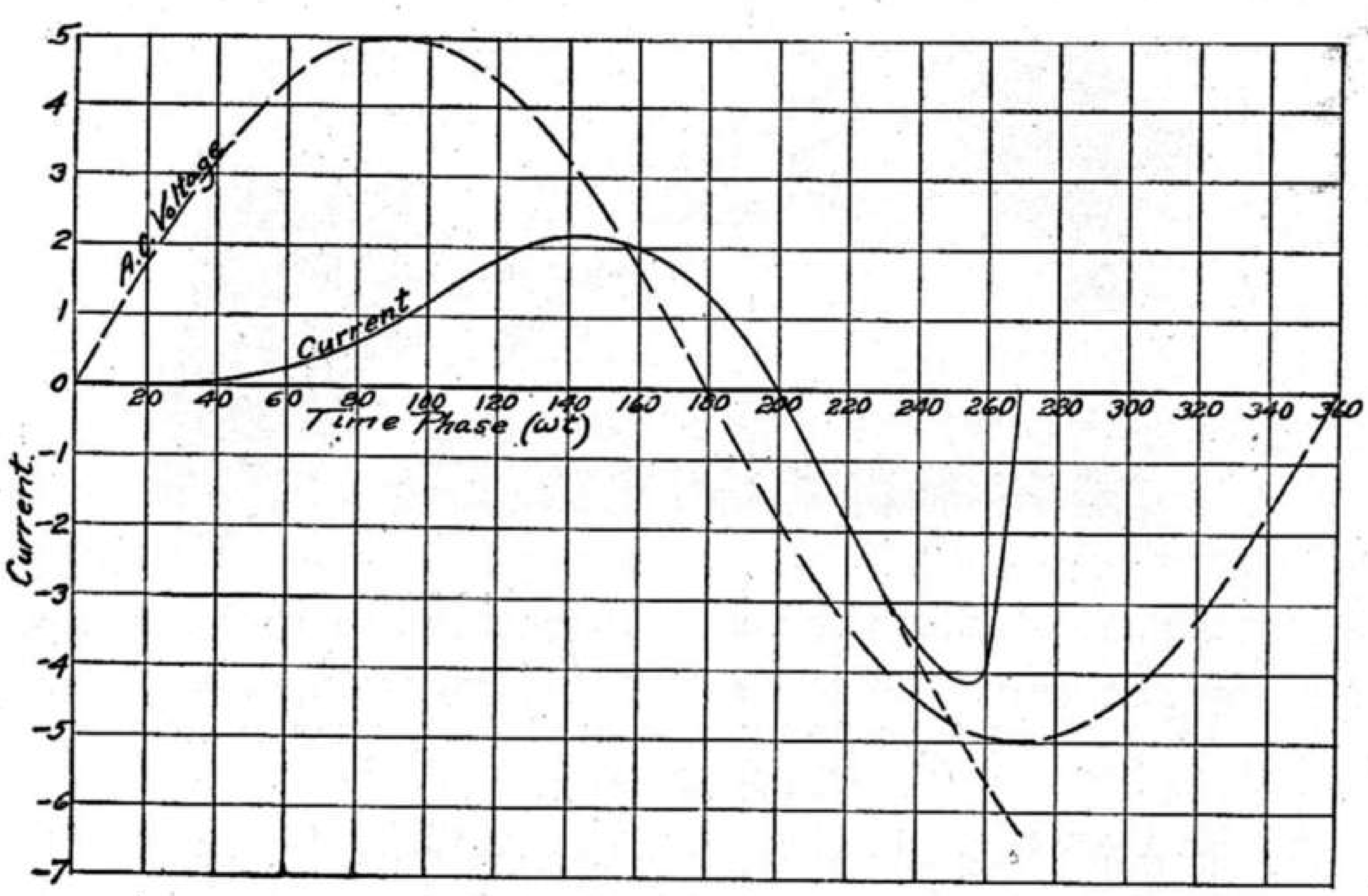


Fig. 6—Electron current curve corresponding to conditions shown in Fig. 5.

The efficiency obtained with standard, cylindrical element triodes as triplers is about ten per cent. The efficiency gain by using a magnetic field varies but has so far been found to be at least three times that obtained without magnetic fields.

Two advantages result from the use of frequency multipliers. The power obtainable with a tube used as a frequency multiplier is many times greater than that which it would deliver as a pendulum oscillator. Frequency control circuits of great accuracy may be employed.

Frequency Control

One of the advantages of very high frequencies for communication purposes is the insignificant width of the modulation band as compared with the frequency of the carrier. This makes it possible to consider a great number of communication channels within frequency limits only a few per cent apart. In order that full advantage may be taken of this situation it is, however, clear that as the carrier frequency is increased its relative stability must also be increased. Aside from this consideration, very accurate frequency control is required to permit maximum selectivity in the receiver in order to obtain optimum signal-to-noise ratio. The transmitters have been required to provide stability sufficient for reception by means of very selective superhetrodyne receivers, without loss of signal quality. Special efforts have been made to produce oscillator outputs as free as possible from undesirable ampli-

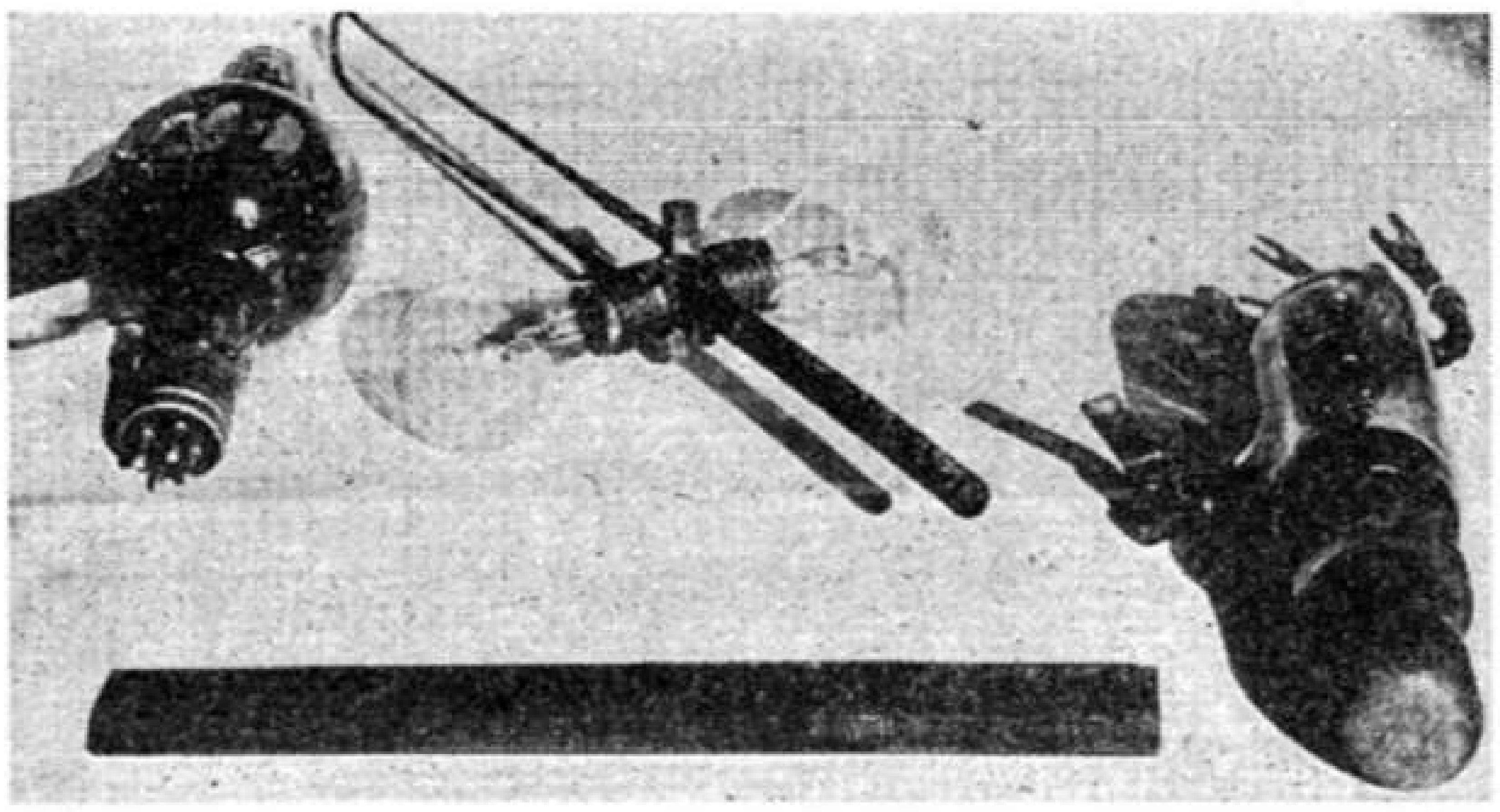


Fig. 7—Left: UX-852 transmitting tube; very useful all-around tube for triode feed-back circuits (Fig. 1), triode pendulum, and frequency multiplier circuits.

Middle: 300-600 megacycle wavemeter and output indicator. Note the two 50-watt load lamps.

Right: RCA-846 (UV-846) water-cooled tube, useful for triode feed-back circuits (Fig. 1) and for frequency multipliers.

tude and frequency variations. Since the difficulties of eliminating these disturbances increase in proportion to the oscillator frequency, the utmost of every available means for frequency stabilization had to be mobilized. Vital circuits must be well shielded against electric or magnetic influences of variable character. It is also very important that the frequency determining parts of the circuit be mechanically separated from their surroundings in order to avoid disturbance from vibrations. In coupling up with output circuits such as transmission lines and antennas, great care must be taken that a minimum of coupling is being used. The reaction from variation in the constants of such circuits, due to wind, precipitation, etc., will otherwise become very disturbing. Self-bias, by means of leak resistances and self-rectification, often results in a tendency to maintain constant tube impedance if introduced in correct proportions in various branches of the tube circuit.

It has often been found necessary to provide smoother anode potentials than normally required at the lower frequencies. Variations in the direct-current supply have been eliminated by means of a regulator consisting of a combination of resistors with a vacuum tube, Figure 16. The grid of the regulator tube is connected to a potentiometer inserted between the direct-current power supply and ground through a source of constant negative bias such as a battery. The function of this bias source is to overcome the positive voltage drop in the potentiometer so that the grid may be maintained at proper operating potential. The anode of the regulator tube draws current from the direct-current power supply through a resistor. The oscillator power is supplied through the same resistor. As an example, an increase in voltage across the direct-current power supply makes the grid of the regulator tube less negative. This increases the current through the common regulator resistor through which both the anode of the regulator tube as well as the anode of the oscillator are supplied. An increase in the voltage drop across the regulator resistor thus takes place. If the device is properly adjusted, the rise in voltage is completely compensated by the drop across the regulator resistor. A front view of such a regulator device is shown at the right in Figure 14.

In addition to such measures it is very desirable to incorporate special frequency controlling devices such as crystals and low power factor tank circuits. Since crystals, of reliable performance above a few megacycles, are difficult to obtain, it is necessary to use many stages of frequency multiplication in conjunction with this type of master oscillator. Low power factor tank circuits can be applied more directly and, since they otherwise compare favorably with crystals, they are more practicable as frequency stabilizers at very high frequencies.

MODULATION

In modulating an oscillator it is sometimes quite difficult to obtain pure amplitude modulation which is not distorted by variations in phase or frequency of the oscillation. This difficulty is rather outstanding with the electron pendulum type oscillators.

Higher degrees of purity may, however, be obtained by resorting to compound modulation, i.e., by applying the modulation energy in at least two different ways and in such a manner that components representing undesirable modulation effects are cancelled. In a Barkhausen oscillator it is, for instance, possible to obtain amplitude modulation substantially free from frequency variations by modulating the plate and grid cophasially with correct proportions of modulating voltage. An increase in the positive grid potential will tend to increase the electron velocity while a simultaneously applied decreased negative potential on the plate will increase the length of path. The frequency of the electron oscillation may thus be kept constant while the flow of the electron current is being modulated. In order to obtain linear amplitude modulation over as large a range as possible, the power output of the nonmodulated carrier must, of course, be reduced since the maximum output of electron oscillators is very definite.

In master oscillator frequency multiplier types of transmitters, undesired frequency modulation is less prevalent, but may sometimes still be desirable to eliminate inasmuch as any variation in the load on the master oscillator will influence its frequency stability. Compound modulation, of various types, may thus be used to advantage.

One very effective way of producing amplitude modulation is to control the power output by interposing a modulator between the transmitter and the antenna. For producing a steady tone, such as required for interrupted continuous wave telegraphy, a commutator across the transmission line is very effective. For more universal purposes a vacuum tube circuit is, however, required. At frequencies above 200 megacycles most vacuum tubes now available are not capable of furnishing efficient conditions for electron transit. In the description of electron pendulum oscillators it was pointed out that the orbital motions of the individual electrons are subject to decay as they deliver their energy to the external circuit. In the case of an absorber the electrons must instead absorb energy from the external circuit and deposit the so acquired kinetic energy in the form of heat on the electrodes or the electrons must be so organized that they will serve efficiently as intermediary links by which the energy is efficiently directed into resistive load circuits. If the electrons themselves are to be made to absorb energy, conditions must be set up which give to the electrons a natural period, or the tendencies for such a period, near the period of the energy to be absorbed. In such a case, the orbital motion of the electrons will be of increasing amplitude so that its kinetic energy will increase. This principle has also been verified in the development of apparatus for the production of high speed ions for the purpose of bombarding atomic nuclei. Periodic oscillations of increasing amplitude are then given to ions instead of electrons.[3]

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[3] E. O. Lawrence and M. S. Livingston, "The Production of High Speed Light Ions Without the Use of High Voltages," *Phys. Rev.*, April 1, (1932).

CIRCUIT CONSIDERATIONS AT ULTRA-HIGH FREQUENCIES

If the electromagnetic field, established around an electrical circuit carrying oscillating energy, has dimensions comparable to the wavelength, energy will be radiated.

Radiation may be reduced by using a balanced or symmetrical circuit, one whose adjacent, corresponding parts give rise to electromagnetic fields of equal amplitudes at opposite phase. The circuit can actually be built symmetrical as is done in push-pull circuits or as in two-wire transmission lines. An originally nonsymmetrical circuit may be located near a conductive surface, Figure 8.

In the ultra-high-frequency technique, linear conductors are often used for tuning instead of circuits with lumped constants. The relative merits of various combinations of tuning circuits may sometimes be judged by the total number of resonance points obtained. The fewer

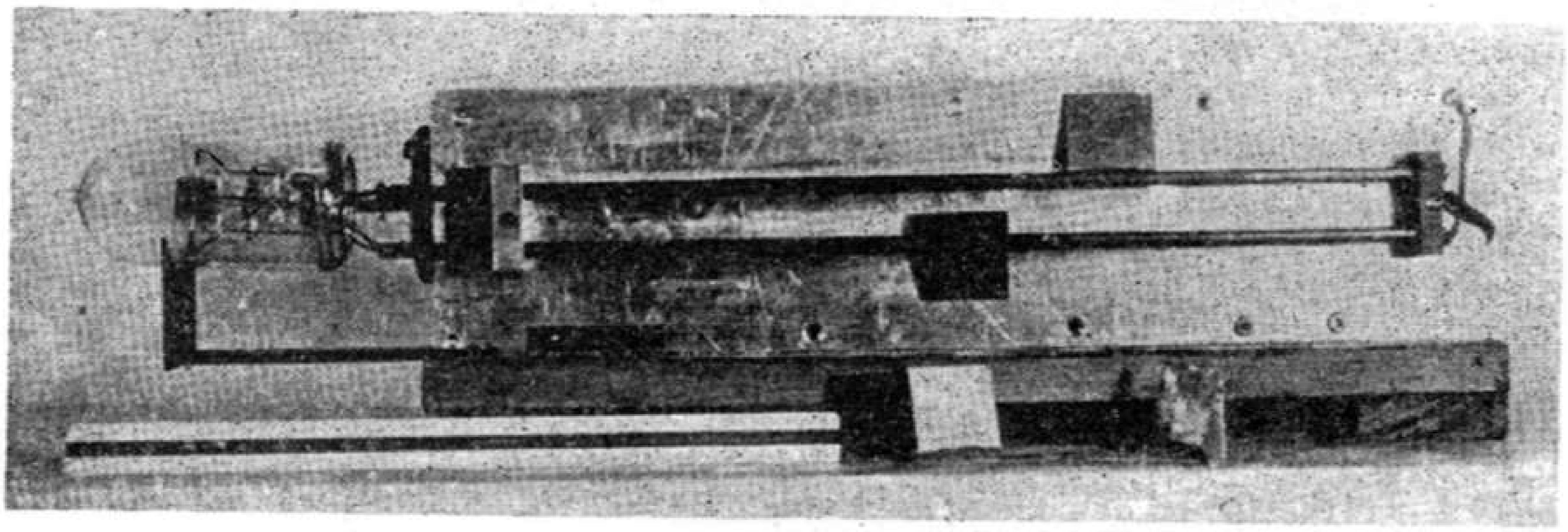

Fig. 8—FP-126, single tube, triode pendulum oscillator. Note the arrangement of the nonsymmetrical circuit near a shield and the wedge-shaped blocking capacitors which serve as tuning sliders. They are wedged between the conductor and the shield. The surface facing the shield is lined with mica.

such degrees of freedom, the better is the circuit. These resonance points arise from many conditions. At very high frequencies, the tube elements and the internal leads of a vacuum tube form an appreciable portion of the total tuned circuit. When continuing these elements and their leads with linear conductors, of dimensions giving constants which match, no additional degree of freedom is obtained. When using external circuits with lumped constants, the total circuit does, so to speak, more definitely consist of several distinctly separated reactance components. These components may neutralize each other in various combinations, creating several resonance points. An additional source of multiple degrees of freedom is also provided by the coupling phenomena created between the various circuits by the capacity combinations between the vacuum tube elements. This effect adds resonance points to linear tuning systems as well as to tuning systems with lumped constants. The resonance points so far referred to, are usually quite close in frequency. The linear type of tuning circuit may, in addition to these, respond to octaves or harmonics of the frequency in which they are fundamentally tuned.

The choice of tuning method is thus determined by many factors. For low frequencies, the linear tuning method becomes impracticable on account of the large physical dimensions required. As the frequency is increased and it becomes possible to use linear tuning, a great number of harmonics may be obtained if the oscillator is still capable of producing an output at the harmonic frequency. By using circuits with lumped constants the harmonic feature may be more easily avoided. The trouble with coupling frequencies may be minimized, or avoided, by so adjusting the circuit that only one of these resonant

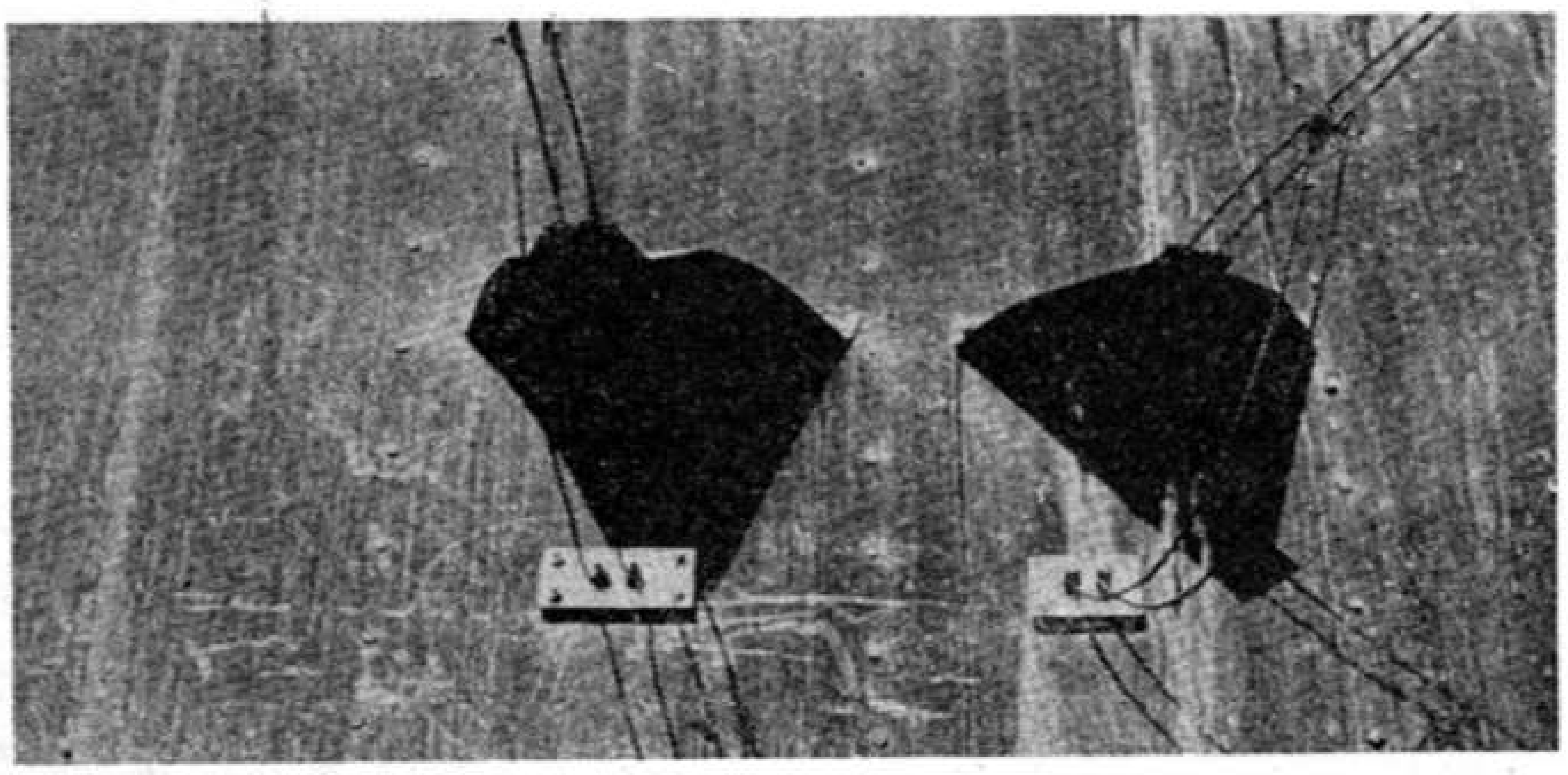

Fig. 9—Transmission line lead-in detail, showing high impedance metallic suspension links sometimes called "metallic insulators."

frequencies conditions, such as voltage and phase, become of controlling influence. At still higher frequencies, where special methods are used and in which the direct-current potential of the electrodes, in a larger measure, controls the frequency, the choice of tuning methods becomes more arbitrary. It may then be determined by other factors such as mechanical features, cost, space required, etc. When the frequency is so high that the first voltage nodal point appears on the lead inside the glass envelops of a vacuum tube, or in some other inaccessible place, the external circuit must be given characteristics equivalent to the addition of a conductor extending half a wave, or a multiple thereof, from this nodal point. Such arrangements are especially successful in master controlled circuits which are void of the ability of self-oscillate.

Linear conductors may, at very high frequencies, replace insulating supports. Such conductors must then be given a certain length so that their impedance is very high at the point of support. For this reason they must also be arranged to be nonradiating in the same manner as linear tuning circuits. A quarter-wave conductor with one end grounded will have high impedance at the other end. For the support of a push-pull circuit a pair of such conductors may be used. Such a pair then corresponds to a U-shaped conductor half a wave long from end to end, with an electrically neutral point at the bend. The losses incurred from the use of these metallic insulators are usually much lower than obtainable with insulating material. Their mechanical strength is superior and their disturbing effect upon the electrical circuit is

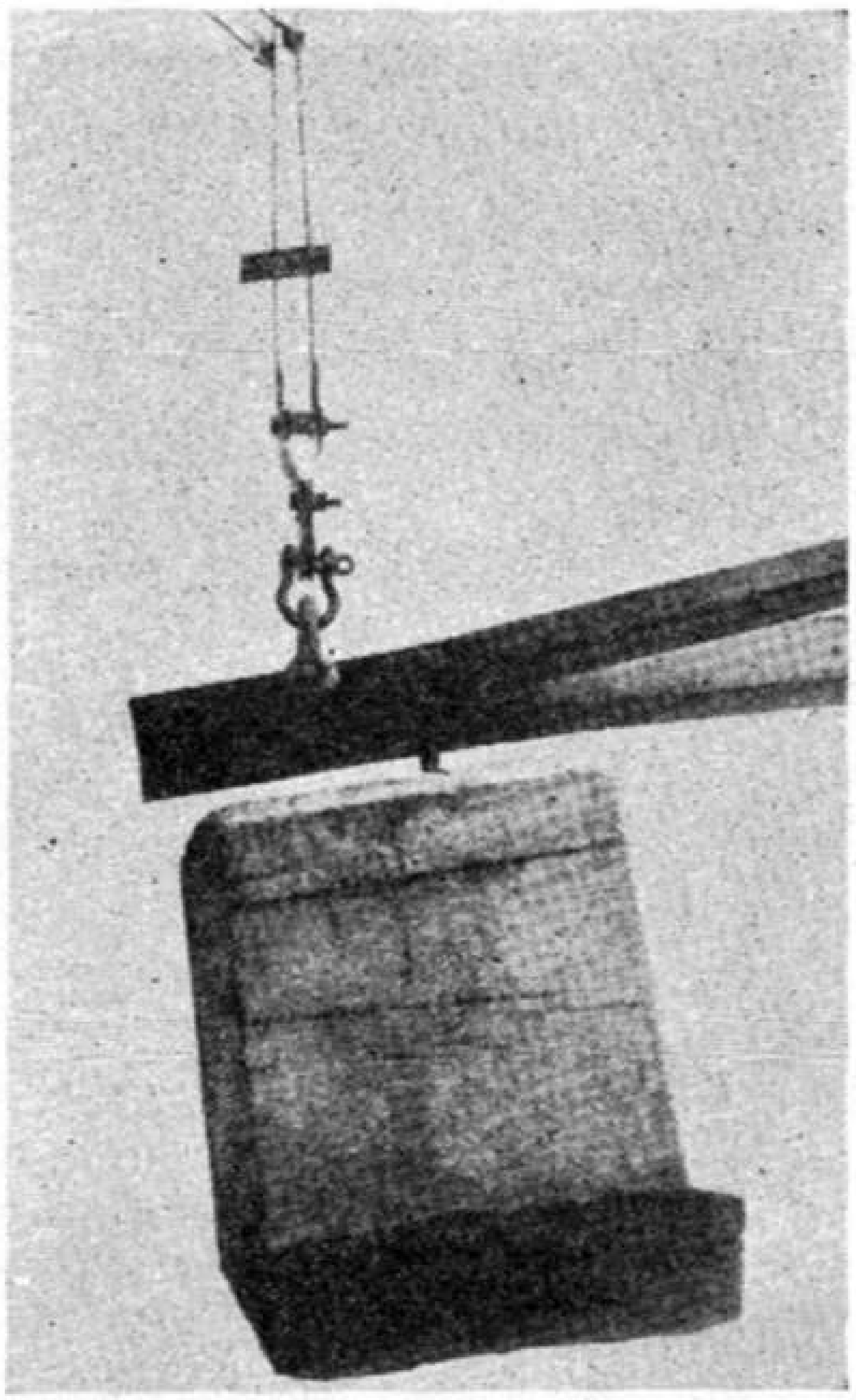

Fig. 10—Bend in a transmission line showing application of metallic insulator.

smaller. They have been found particularly useful in transmission-line work down to frequencies as low as fifty megacycles. Applications are illustrated in Figures 9 and 10.

It has been found that stranded wires cause very high losses. The reason is that the twisting increases the inductance of the individual strands. At very high frequencies a considerable portion of the current will, therefore, force its way over the shorter and lower reactance path from strand to strand either capacitively or conductively. Since such conductors are seldom clean, the losses at such crossovers are very high. This point requires special consideration in connection with some of the standard transmitting tubes which are equipped with stranded connecting leads. It is best to eliminate these leads whenever possible.

For obtaining a direct grounding effect on the filaments of a tube it is sometimes necessary, for reasons already mentioned, to extend the length of these leads to make them one-half wave long. In less conventional circuits certain improvements in the phase and voltage conditions between the electrodes may be obtained if it is possible to tune the filament circuit. Whether linear conductors or circuits with lumped constants are used, the easiest way of supplying the filament heating current is to make the radio-frequency conductor of tubular material and to locate the leads for the heating current inside this conductor. Small blocking condensers should then be used at the filament end to

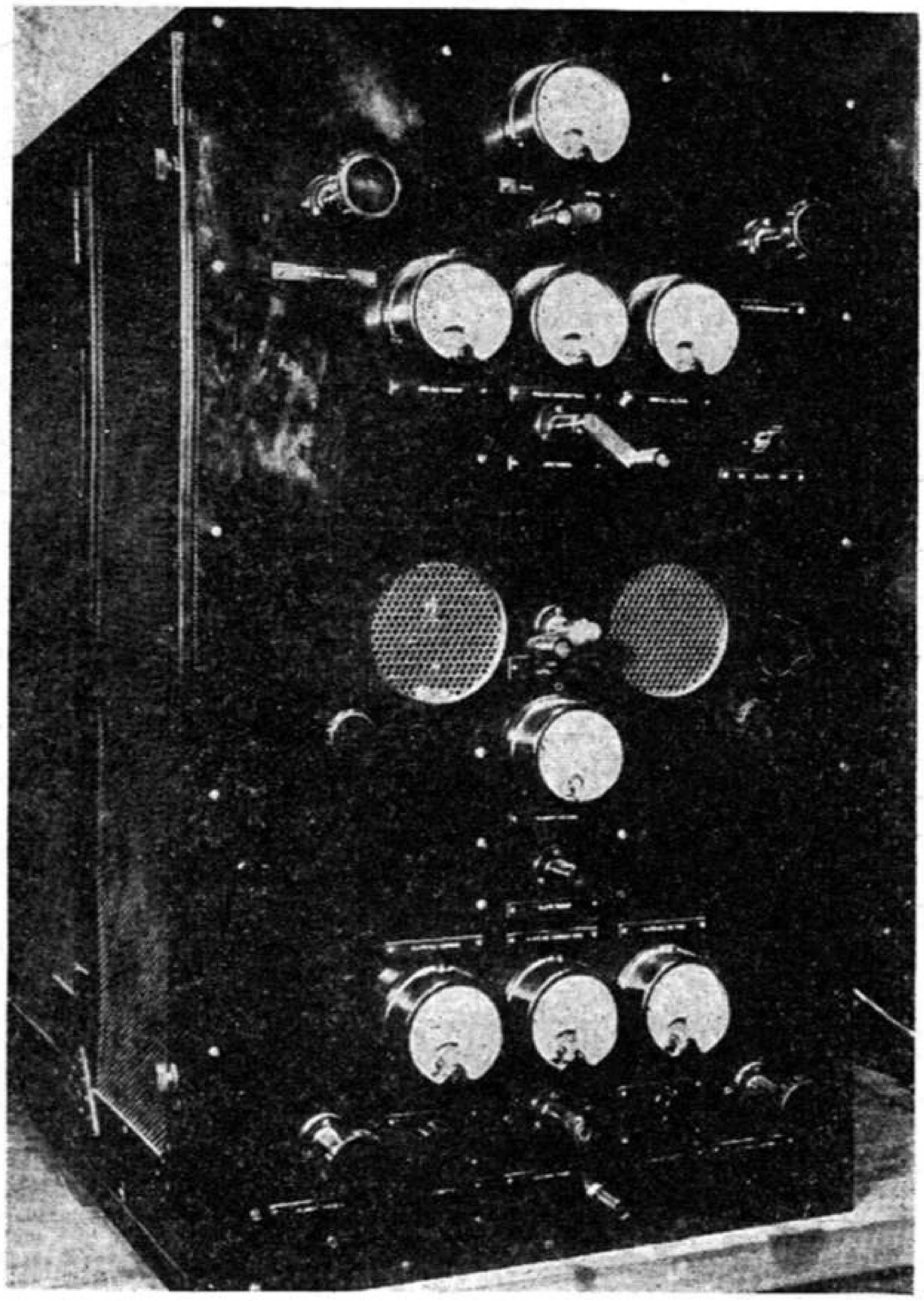

Fig. 11—Front view of 462-megacycle, 6-watt output, UX-852 tube, push-pull transmitter of the triode pendulum oscillator type.

prevent radio-frequency currents from entering the heating circuit. Such arrangements are illustrated in Figure 18.

When using larger tubes, of the water-cooled type, the water can be supplied to the tube jackets through metal tubing which also serves as tuning conductor. The supply and return water may be handled either through concentric or independent tubings. The latter is sometimes convenient in that the two parallel tuned circuits thus obtained allow independent branches for tuning and coupling. (See Figures 17 and 18.) If these leads also carry high direct-current potential the water circuit is continued through a rubber hose of adequate length. This hose is usually attached at a point neutral to radio-frequency voltages.

During experimental work it may often be found difficult to get a new circuit going. Since it is much easier to study the sources of trouble if a circuit is oscillating, it is sometimes valuable to use an auxiliary trigger or a "catalyst" circuit. The functions of such a circuit are manifold. The conductive losses of the oscillator circuit may be too high. There may be an excessive radiation resistance or some phase and voltage condition may need correction. A catalyst circuit

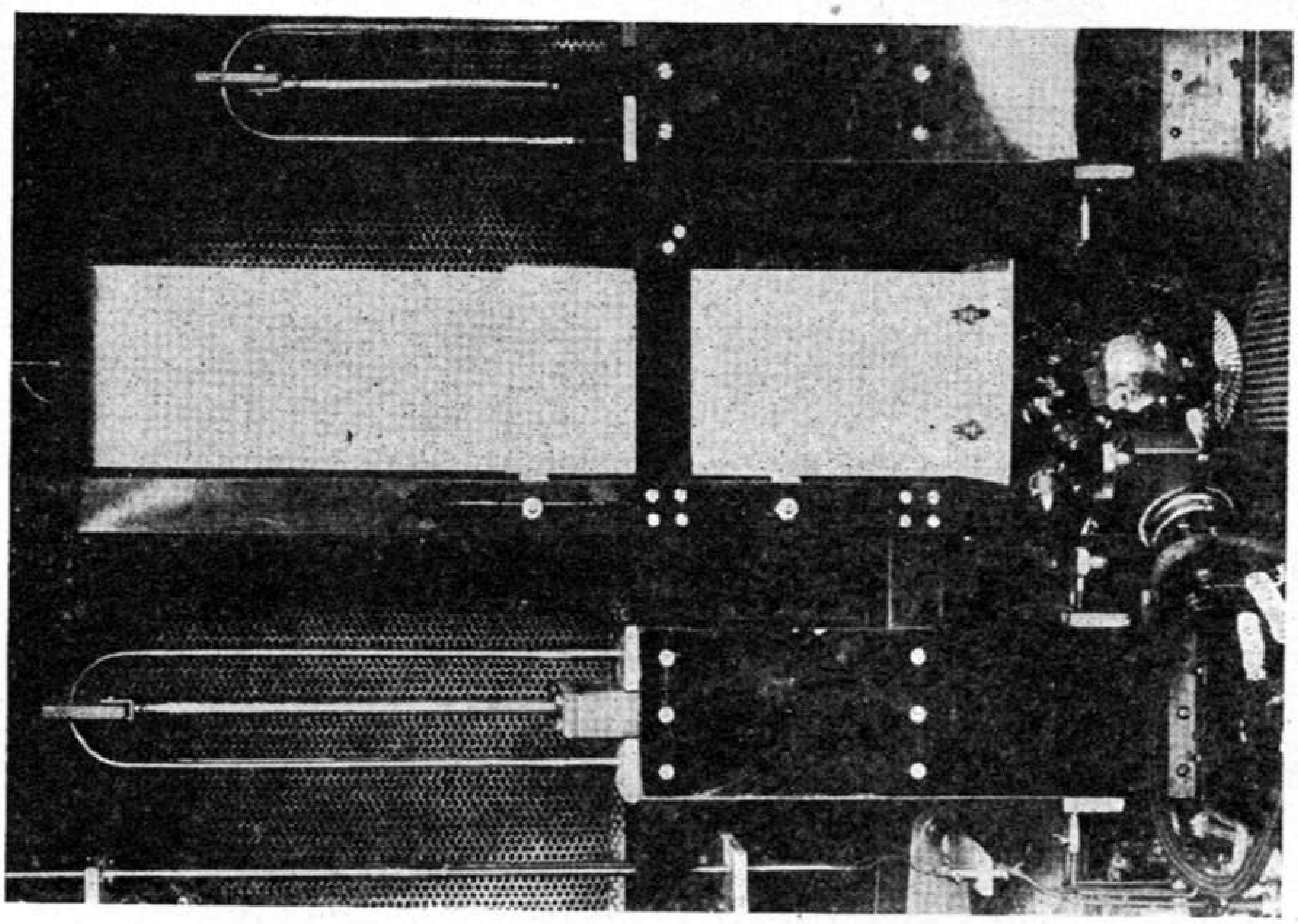

Fig. 12—Side view of 462-megacycle, 6-watt output, UX-852 tube, push-pull transmitter of the triode pendulum oscillator type, showing "catalyst" circuit.

has, therefore, no definite form but must be made up to suit the suspected condition. A wide strip of copper, a half wave long, may be bent around in different ways and placed in various positions near the tubes or the associated circuits, Figure 12. If, for instance, the trouble consists of too high resistance in the flexible tube leads, some of the external circuit tuning may be taken over by the catalyst circuit since it may be placed in such a position that it is capacitively coupled to the tube elements directly through the glass envelops without the aid of the leads. Phase conditions may sometimes be corrected by means of tuned loops. Most forms of catalyst circuits are applicable in reducing radiation. The location of shields at certain distances from the oscillator may also sometimes produce desired results.

EXAMPLE OF TRANSMITTING EQUIPMENT

In order to obtain as complete design data as possible the experimental models have in some cases been developed to such a point that they would, as nearly as possible, conform with the exacting requirements of commercial operation. Many of the considerations in such designs have already been discussed in a general way. Examples of such equipment need, therefore, only a brief description.

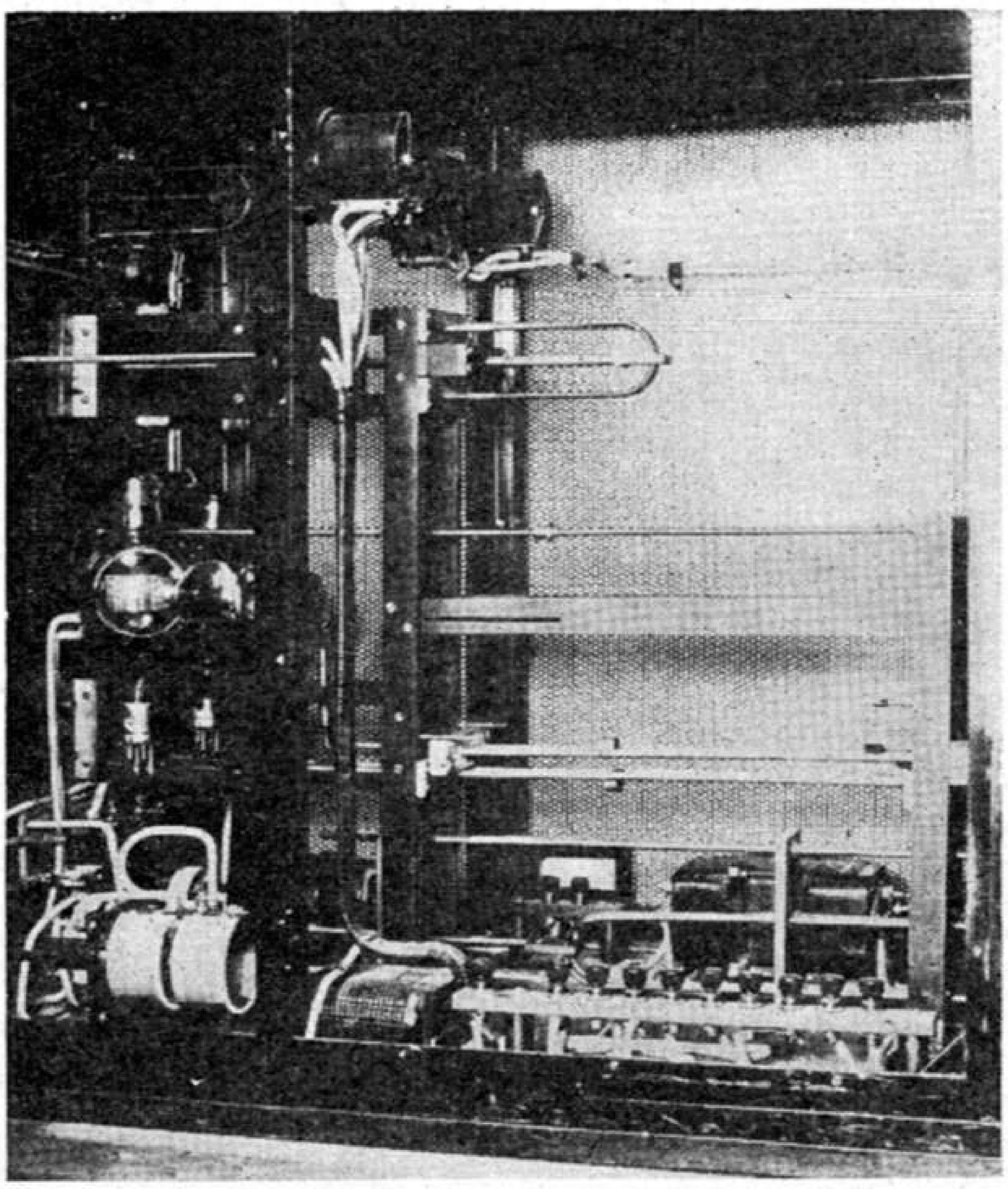

Fig. 13—Side view of 462-megacycle, 6-watt output, UX-852 tube, push-pull transmitter of the triode pendulum oscillator type, cathode circuit tuning is here being used.

1. UX-852 Barkhausen Transmitters

The first two transmitter units were built to operate at a frequency of 462 megacycles and a wavelength of 65 centimeters. For about a year they were used for two-way telephony between Rocky Point and Riverhead. These transmitters, which are shown in Figures 11, 12, and 13, are of the triode electron-pendulum type. Each transmitter consists of a pair of UX-852 tubes, operated in push-pull. The tuning circuits are of the linear conductor type and of the trombone variety. In one transmitter only the plate and the grid circuits were tuned. The filament heating current was supplied through choke coils. The oscillator was equipped with a catalyst circuit, Figure 12. This circuit consisted of sections of three-inch wide metal strips forming a U of variable length similar to a trombone circuit. At the end of this U were flanges, each facing one of the oscillator tubes. As an alternative the other transmitter was equipped with a tuned cathode circuit, Figure 13. On account of the heating current leads inside, the filament tuning conductors cannot conveniently be of the trombone type but must instead be tuned by a sliding connector. It made little difference which circuit was coupled to the load. The power was taken from the plate circuit in this case. Potentiometers for individual control of the direct-current electrode potentials of the two tubes were also introduced. All tuning, coupling, and potential regulation was performed

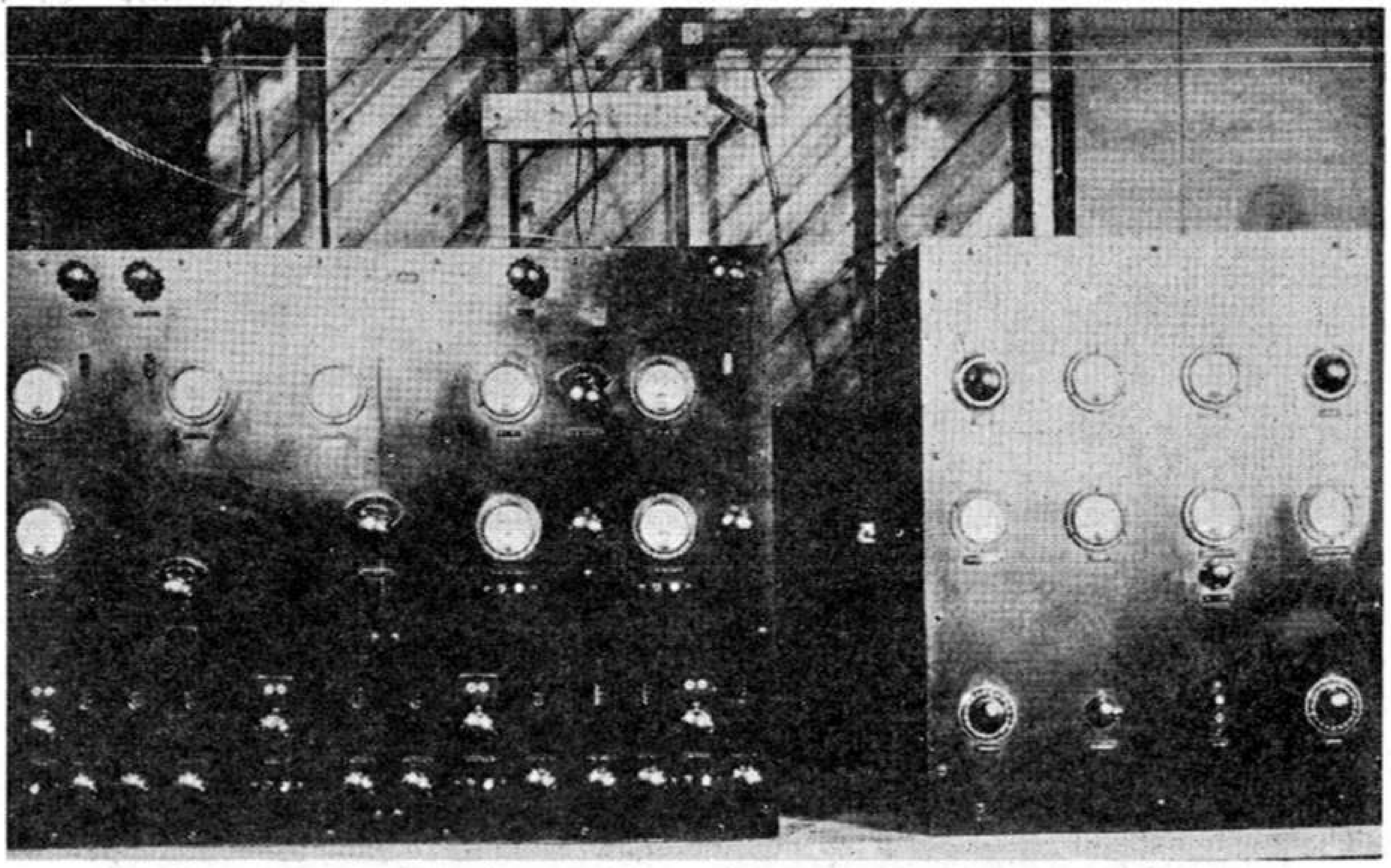

Fig. 14—Left: Front view of 432-megacycle, 15-watt output transmitter, consisting of a 144-megacycle oscillator, a buffer amplifier, a frequency tripler, and an amplitude modulator of the absorber type. All stages are of the push-pull type, using UX-852 tubes.
Right: Front view of plate voltage regulator for the plate supply of the oscillator stage and the buffer stage.

from the front of the panel. Radio-frequency ammeters were inserted at points neutral to radio-frequency voltages. It was due to the desirability of keeping these meters in a fixed position and on the front of the panel, that the circuits had to be looped over and be tuned by trombones.

This transmitter was compound modulated. A special modulator, shown in Figure 23, was built for this purpose.

The positive grid voltage required at 462 megacycles was 500 volts. The negative plate voltage was 125 volts. The normal filament voltage is ten volts for the UX-852 tubes. In order to obtain suitable emission of 250 milliamperes per tube it was necessary to cut the filament voltage down to between seven and nine volts. Due to the great heating gradient from the grid, the filament emission would at times become unstable. Some tubes would eventually become stable at about nine volts. This phenomena was credited to the sensitivity of the thoriated filaments used in this type of tube. A power output of six watts was obtained from these transmitters.

2. UX-852 Frequency Multiplier

As a result of the experiments with frequency multipliers, a transmitter as shown in Figures 14, 15, and 16 was built. It is of the push-pull type throughout. The first stage may either self-oscillate or be driven at about 144 megacycles. The output from this circuit drives

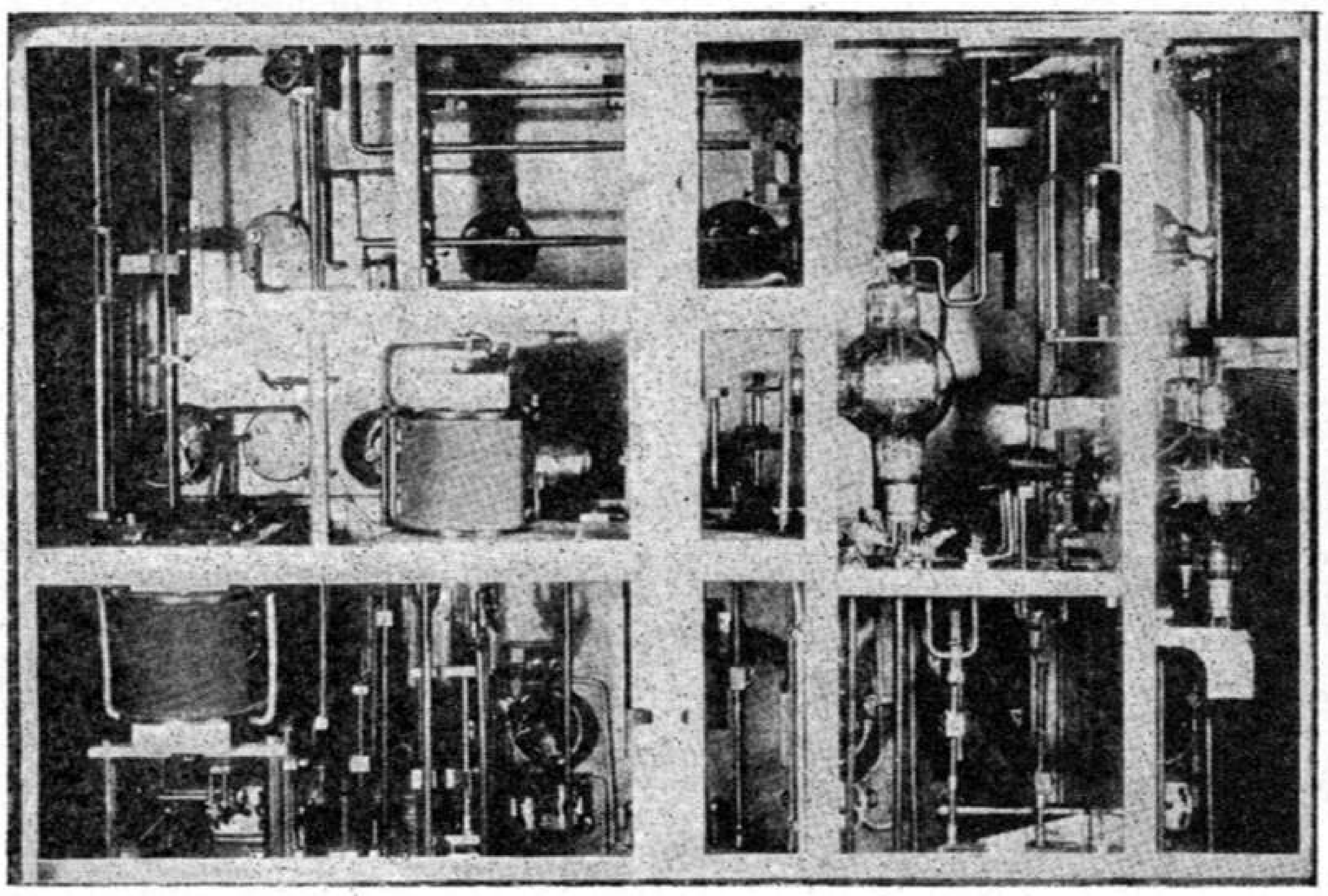

Fig. 15—Rear view of the 432-megacycle, 15-watt output, multiplier type transmitter shown on the left in Fig. 14.

an amplifier, or buffer stage, which gives a power amplification of two to one. This is the best amplification that could be obtained with the UX-852 tubes at this frequency. The power from this buffer is fed into a tripler circuit which delivers 432 megacycles output at about ten per cent efficiency. The tripler is equipped with means for producing an axial magnetic field of about 150 gauss. The power output obtainable from this transmitter is fifteen watts. All the tube elements are tuned and the tuning circuits are of the linear conductor type and of both the trombone and slider variety, depending upon the need.

One of the reasons for studying frequency multipliers has been the need of greater frequency stability and the particular adaptability of this method to frequency control. Crystal control was one of the first methods to be tried. An auxiliary control circuit was built which con-

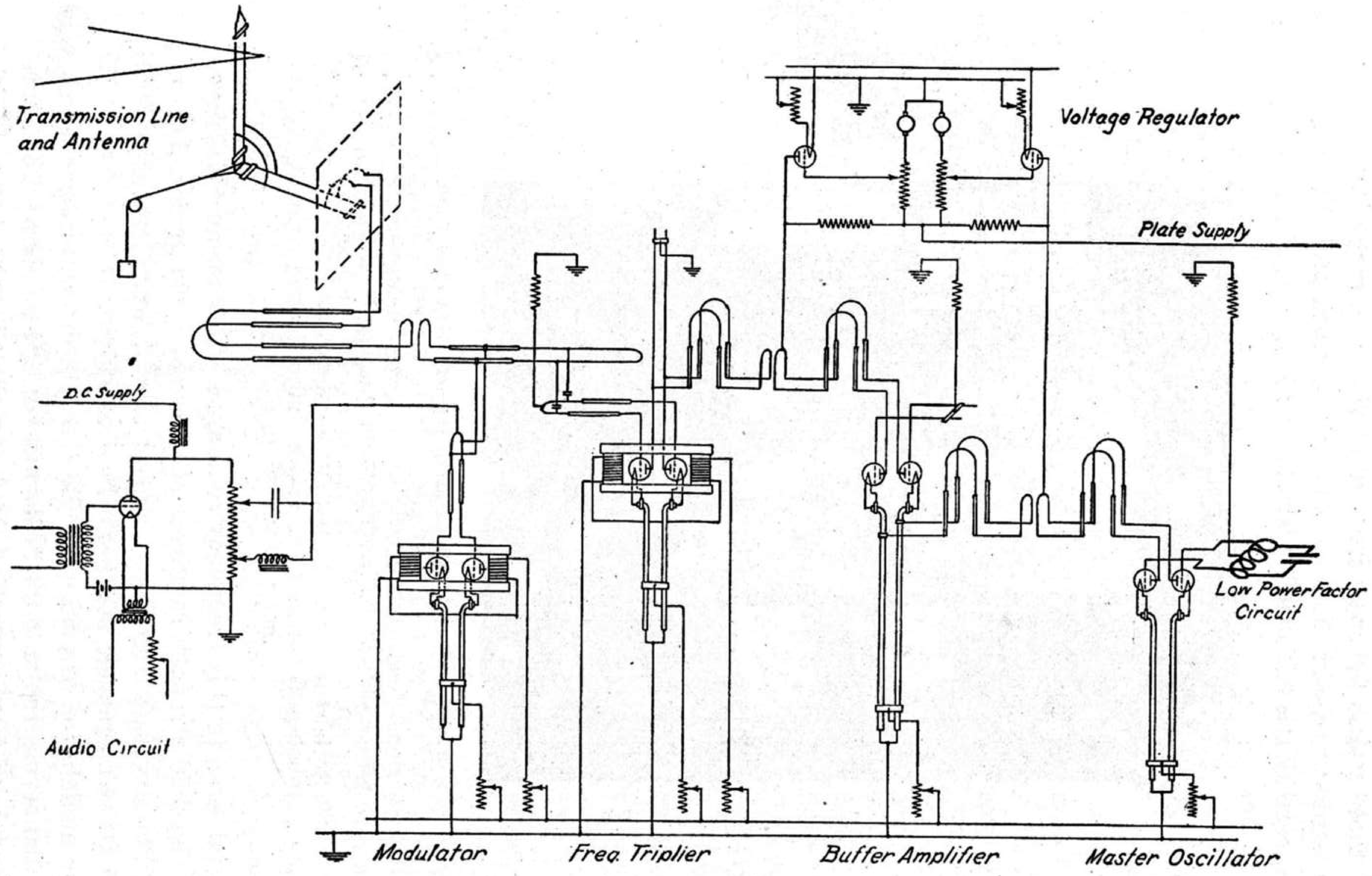

Fig. 16—Schematic wiring diagram of the 432-megacycle, 15-watt output, multiplier type transmitter shown in Figs. 14 and 15.

sisted of a crystal oscillator operating at about two megacycles followed by six stages of frequency multipliers. The crystal circuit and the first four stages were single sided circuits employing UX-210 tubes. The last of these stages fed into the combination of a single UX-860 buffer and a single UX-852 doubler driving a push-pull UX-852 tripler circuit, raising the frequency from 48 to 144 megacycles. It was found

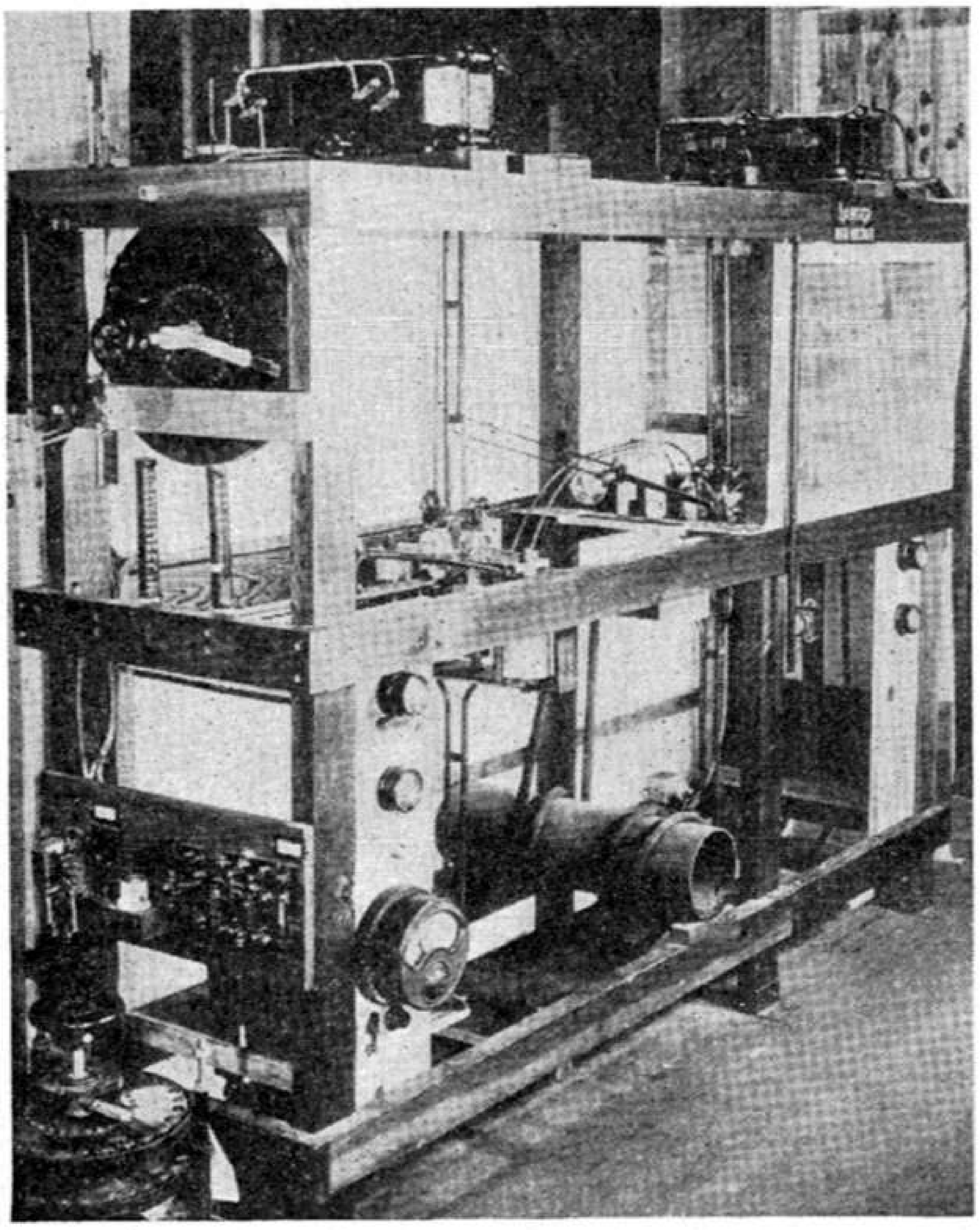

Fig. 17—Frequency multiplier transmitter, consisting of a 137-megacycle, 1500-watt output, triode feed-back oscillator (in the background) and a tripler, with organizing magnetic field, giving an output of 115 watts at 411 megacycles. Both stages use RCA-846, water-cooled tubes in push-pull formation. Note lamp loaded wavemeter (same as in Fig. 7).

beneficial, even in this frequency region, to introduce an axial magnetic field. The field strength required was less than 100 gauss. The output from this auxiliary frequency control circuit was then used to drive the first 144-megacycle stage of the transmitter.

For modulation, a push-pull UX-852 absorber was used which was connected across the antenna transmission line as shown in Figure 16. The length of the connecting leads to the absorber were such that optimum modulation effect would be obtained. These leads were connected to the grids of the absorber which act as modulation terminals.

The plates may be left floating since they have no part in the circuit. The grid and the filament circuits are tuned. The grids are given a positive bias of about sixty volts, which causes them to draw a current of about five milliamperes each at an axial magnetic field of 200 gauss. The modulation voltage as well as the radio-frequency carrier to be modulated were then superimposed upon this grid condition. In this way it was possible to obtain linear amplitude modulation of about 35 per cent.

Numerous arrangements for replacing the complicated crystal drive, with its many multiplier circuits, have been tried. These arrangements consisted of various forms of low power factor circuits connected to the grids of the 144-megacycle oscillator. Some of these arrangements have proved very successful in that stability approaching that of crystals was obtained. Data on such circuits have already been published and further information may be published later.

3. RCA-846 Frequency Multiplier Transmitter

Although the design of a semicommercial model of this apparatus has not been finished, at the time of writing this paper, it appears to have sufficient points of interest to warrant being included among the transmitter examples in its experimental form, Figures 17 and 18. It consists of a push-pull oscillator operating at 137 megacycles furnishing power to a push-pull frequency tripler. The tripler is provided with an axial magnetic field. All the tubes are RCA-846 water-cooled tubes. The tuning circuits are of the linear conductor type and arranged similarly to the circuits for the UX-852 multiplier. The tubular plate tuning conductors also carry the water supply to the plate jackets.

Several optimum circuit combinations, each requiring a different magnetic field, could be obtained. With an input to the tripler of 1200 watts the best output obtained when using a magnetic field was 115 watts at an output frequency of 411 megacycles. The magnetic field required for various circuit arrangements varied between 100 and 300 gauss. When using no magnetic field the best circuit arrangement would give an output of 35 watts.

4. Triode Feed-Back Circuits

Great progress has been made recently in the development of triodes for operation, according to the conventional feed-back method, at very high frequencies. Transmitting tubes have been developed which will give good output up to as high frequency limits as 300 megacycles. (ZP-94 curve in Figure 1.) It is therefore no longer necessary to resort to special methods for frequencies of this magnitude. These developments have, however, also resulted in a proportional increase in the frequency borders of the frequency multiplier method and it is now possible to consider this very stable method in the 1000-megacycle region.

ANTENNAS AND TRANSMISSION LINES

In designing directional antenna systems, choice can be made between two general principles. The first one, which may be called the Hertzian method, consists in redirecting the radiated energy from a

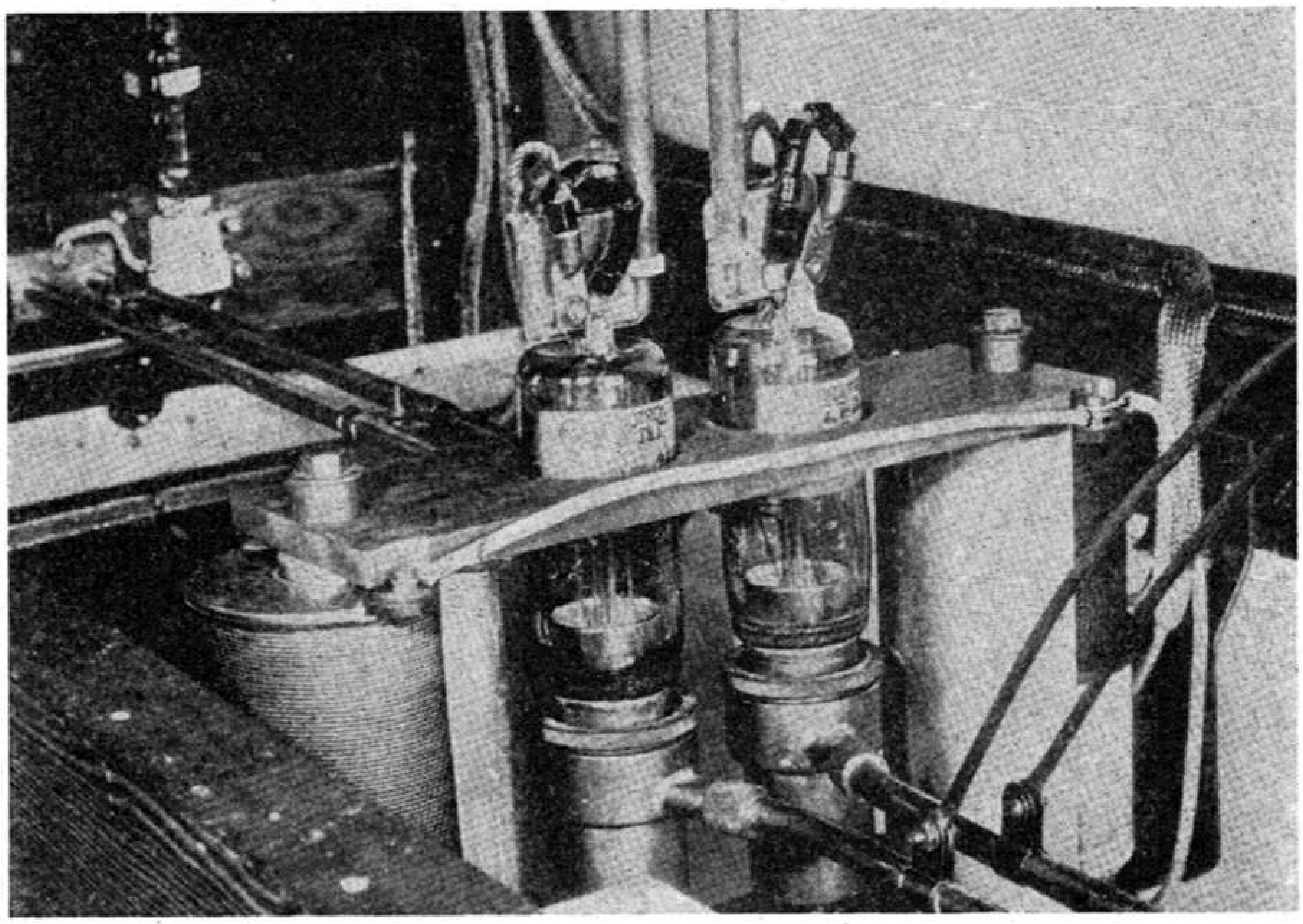

Fig. 18—411-megacycle, 115-watt output, RCA-846 water-cooled tube, push-pull tripler with parallel coil system magnet for producing organizing magnetic field.

single nondirective radiator into one direction. This is done by means of a parabolic, metallic reflecting surface or by means of conductors arranged in a parabolic array. The perfection of the method depends upon the size of the reflector system, measured in wavelengths.

In the second method no reflecting surfaces need be employed. The origin of radiation is instead distributed. A number of radiating elements, such as dipole antennas may be so spaced and phased that they add up very efficiently only in diametrically opposite directions. By further combination, radiation in one of these directions may also be eliminated.

Several years ago the method of combining straight harmonic radiators instead of dipoles was introduced by R.C.A. Communications, Inc.[4] This principle has greatly simplified the details of directive antenna design. Detailed descriptions of such systems have been published previously in the *Proceedings*.[5] As the name indicates, the harmonic wire antennas are based on the standing wave principle. When the frequency is sufficiently high so that it becomes possible to make the length of the radiators on the order of 50 to 100 wavelengths, the radiation attenuation becomes so great that very little energy reaches the far end of the wires. The antenna then becomes unidirectional and aperiodic. This is a great simplification since it makes reflector systems and tuning arrangements unnecessary. An antenna of this type is shown in Figure 19. It is commonly known as a V antenna.

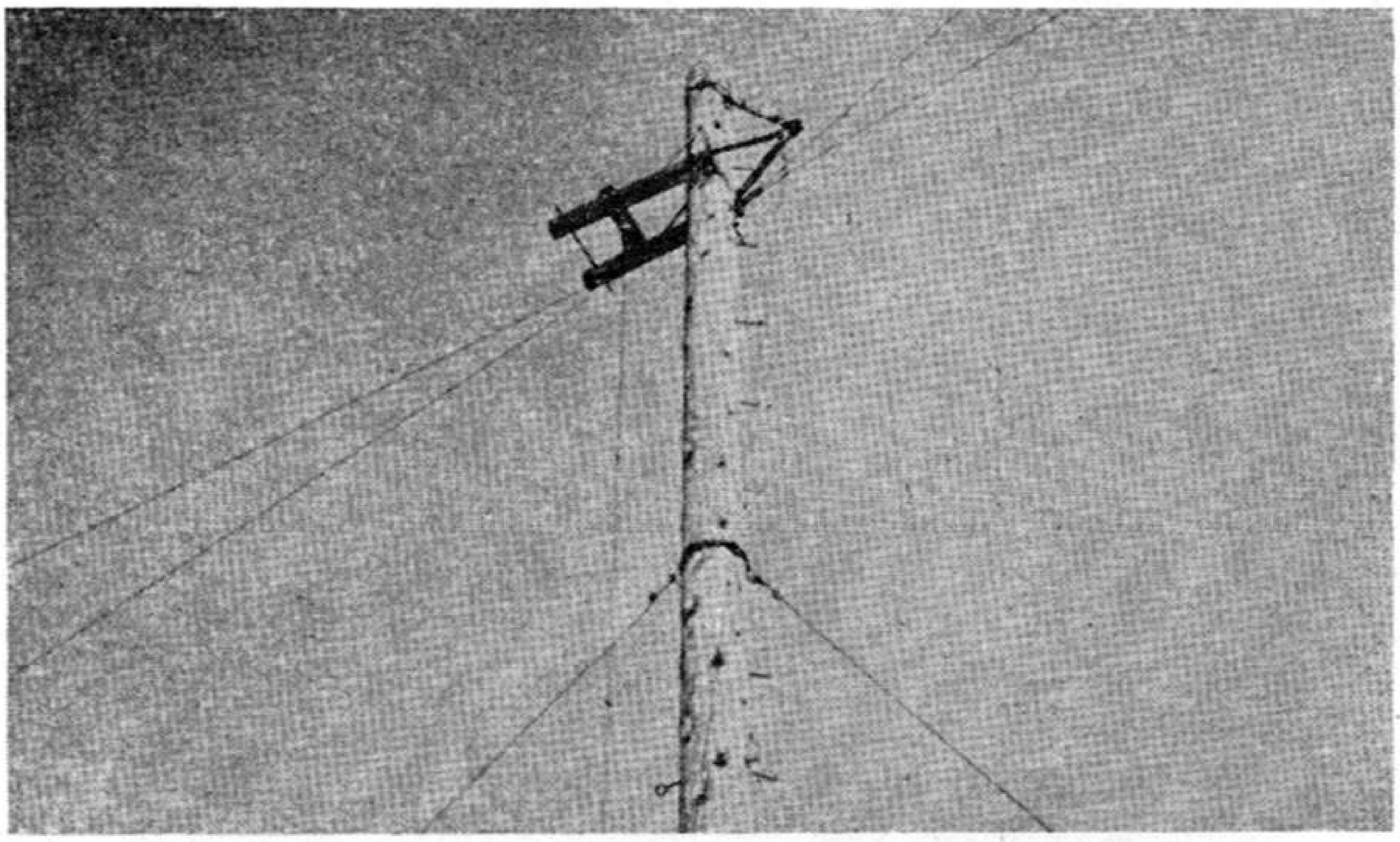

Fig. 19—Feed end of the V antennas.

A V antenna 100 wavelengths long should have an angle of 9.8 degrees between the wires. The power gain, over a doublet, is more than 100.

It may at times be desirable to provide an antenna entirely free from back radiation. Such an occasion may arise when the transmitting and receiving antennas have to be closely located and operate on near-by frequencies. An antenna having a metallic sheet reflector is then desirable since it is more perfectly free from back radiation than other antenna types. In order to avoid curved reflector surfaces, antennas as shown in Figure 20 were designed. This antenna consists of rectangularly bent wires with half-wave distances between the bends. By combining several such wires an arrangement is obtained in which

[4] Lindenblad, U. S. Patents No. 1,884,006 and No. 1,927,522.

[5] P. S. Carter, C. W. Hansell, and N. E. Lindenblad, "Development of Directive Transmitting Antennas by R.C.A. Communications, Inc," *Proc. I.R.E.*, Vol. 19, pp. 1773-1843; October, (1931).

all the vertical elements are free to radiate and are of the same phase, whereas all the horizontal ones have their radiation cancelled by a horizontal member of another wire in juxtaposition. The various bent wires are attached to a common feeder line in pairs, at half-wave intervals. The wires are supported by means of insulators or metal columns at the voltage nodal points. The whole system is mounted in front of either a metal screen or a solid metal sheet at a distance of about a quarter of a wave or an odd multiple thereof.

Some workers have followed the practice of building the transmitter and antenna system together as a single unit. This is undesirable in many cases because the antenna must be at a great height to obtain

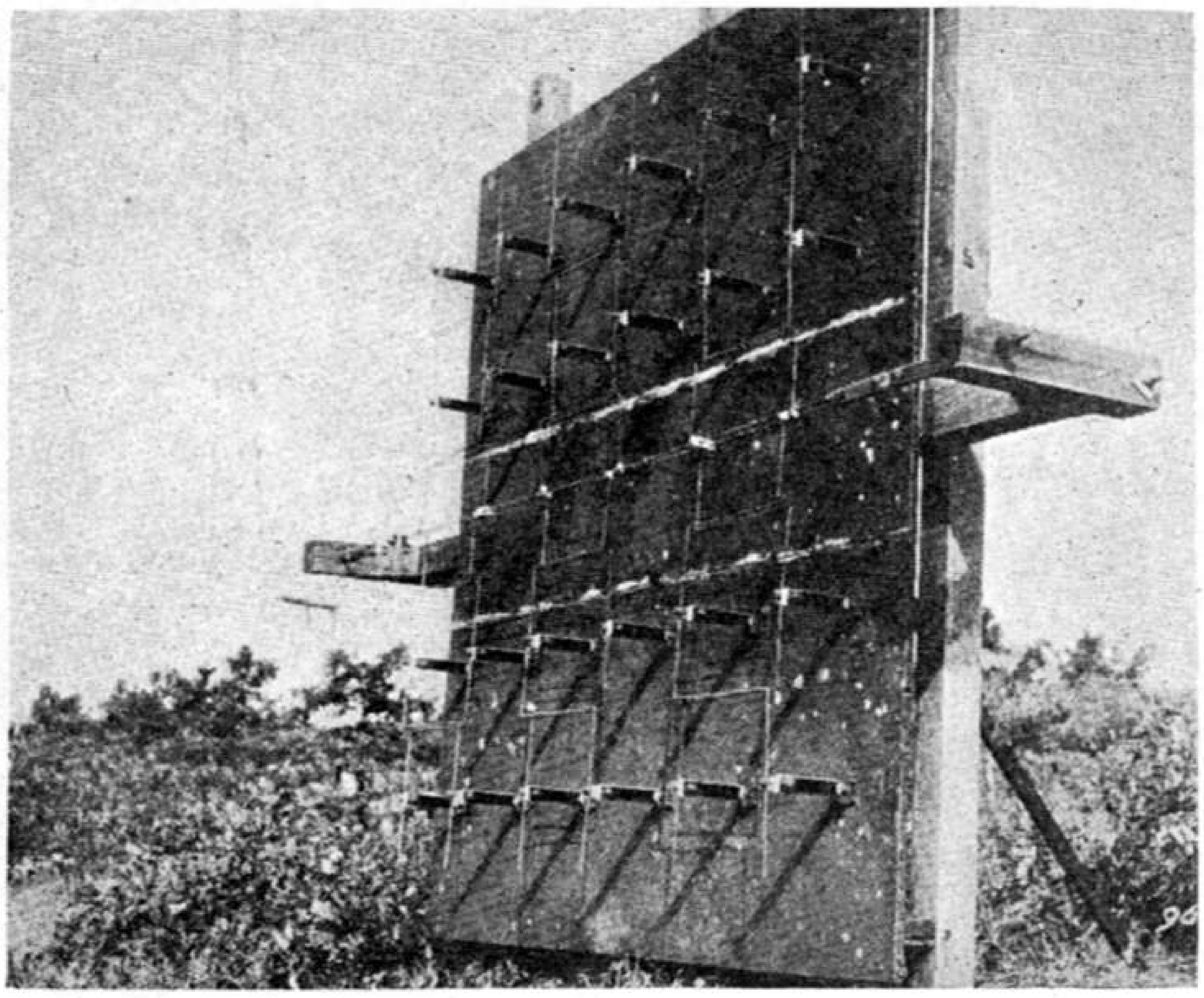

Fig. 20—"Billboard" type, directive antenna.

great range. A transmitter located at the antenna cannot be serviced conveniently. Consequently, it is often desirable to locate the antenna and transmitter some distance apart, requiring the use of transmission lines of considerable length. On most occasions this has been the practice. A study of the characteristics of such lines had therefore to be made. Balanced lines using No. 4 B&S and No. 6 B&S wire were investigated. Inductive coupling to the line under test was employed to minimize the effect of reflections and unbalance in the connecting lines from the transmitter. The measurements on the lines were made with the aid of a sensitive thermogalvanometer which made it possible to use very small capacitive coupling to the wire system, thus avoiding disturbance of the natural capacity and resistance of the line. The relatively large amount of power (100 watts) available from the frequency multiplier transmitter was an important factor in making it possible to use very light coupling between the measuring instrument and the wires. The measurements included determining losses and also velocity variations due to moisture on the wires. The loss measurements were carried out at a frequency of 405 megacycles and the velocity measurements at 422 megacycles.

For No. 4 B&S wires spaced one inch apart the calculated value of the attenuation constant per 100 feet is 0.037. The measured average is 0.045. This corresponds to an efficiency of 91.4 per cent for a 100-foot line and 40.7 per cent for a 1000-foot line. The theoretical value of the attenuation constant for a No. 6 B&S wire is 0.042 per 100 feet and the measured value is 0.050. This corresponds to an efficiency of 90.5 per cent for a 100-foot line and 36.8 per cent for a 1000-foot line. It was found that the difference between losses on clean and weathered wires was too slight to be measured. These measurements indicate that it is practical to use balanced, closely spaced, two-wire transmission lines up to several hundred feet in length. For longer lines, the more expensive large diameter concentric conductor type of line must be chosen if good efficiency is to be maintained.

The presence of spacers, if made of good material and if used sparingly, usually add very little to the loss in dry weather. In wet weather, however, the loss and the reflections caused by such spacers are very serious handicaps. They are avoided entirely by using U-shaped half-wave conductor suspension loops, or "metallic insulators."

During rain the increase in loss from the presence of a water film on the wire was found negligible. The wave velocity along the line did, on the other hand, show a very marked decrease. Weathered and polished wires also showed a very marked difference in their ability to hold water. A horizontal line made of new No. 6 B&S wires with one-inch spacing was found to hold enough water to reduce the velocity by three per cent. The distribution of the water was very beady. The thickness of an evenly distributed water film required to cause this amount of variation in velocity was found by calculation to be 0.008 inch. The distribution of the water on a weathered wire was much less beady and was more evenly distributed. The velocity change for maximum water condition was 0.6 per cent, corresponding to a uniform film thickness of 0.002 inch. The maximum reduction in velocity for a weathered No. 4 B&S wire was 0.5 per cent.

From these values, the velocity change on a more open-wire system such as a V antenna can be calculated. For such a system the velocity change for weathered wires amounts to about 0.2 per cent or less. This is fortunate since the change will ordinarily not have sufficient influence upon the characteristics of a hundred-wave antenna to be serious.

Such variations and even greater ones can, however, be expected during sleet storms. In some commercial installations it will be necessary to provide for sleet melting. There are a number of ways in which this can be done with long wire antennas.

Propagation Tests

The chief purpose of the transmitter equipment which has been developed in accordance with the principles just outlined has been to study propagation in new frequency regions. Since the results of some of these tests are quantitatively described in detail in a paper by B. Trevor and R. George,[6] only some of the results obtained will be given in this paper.

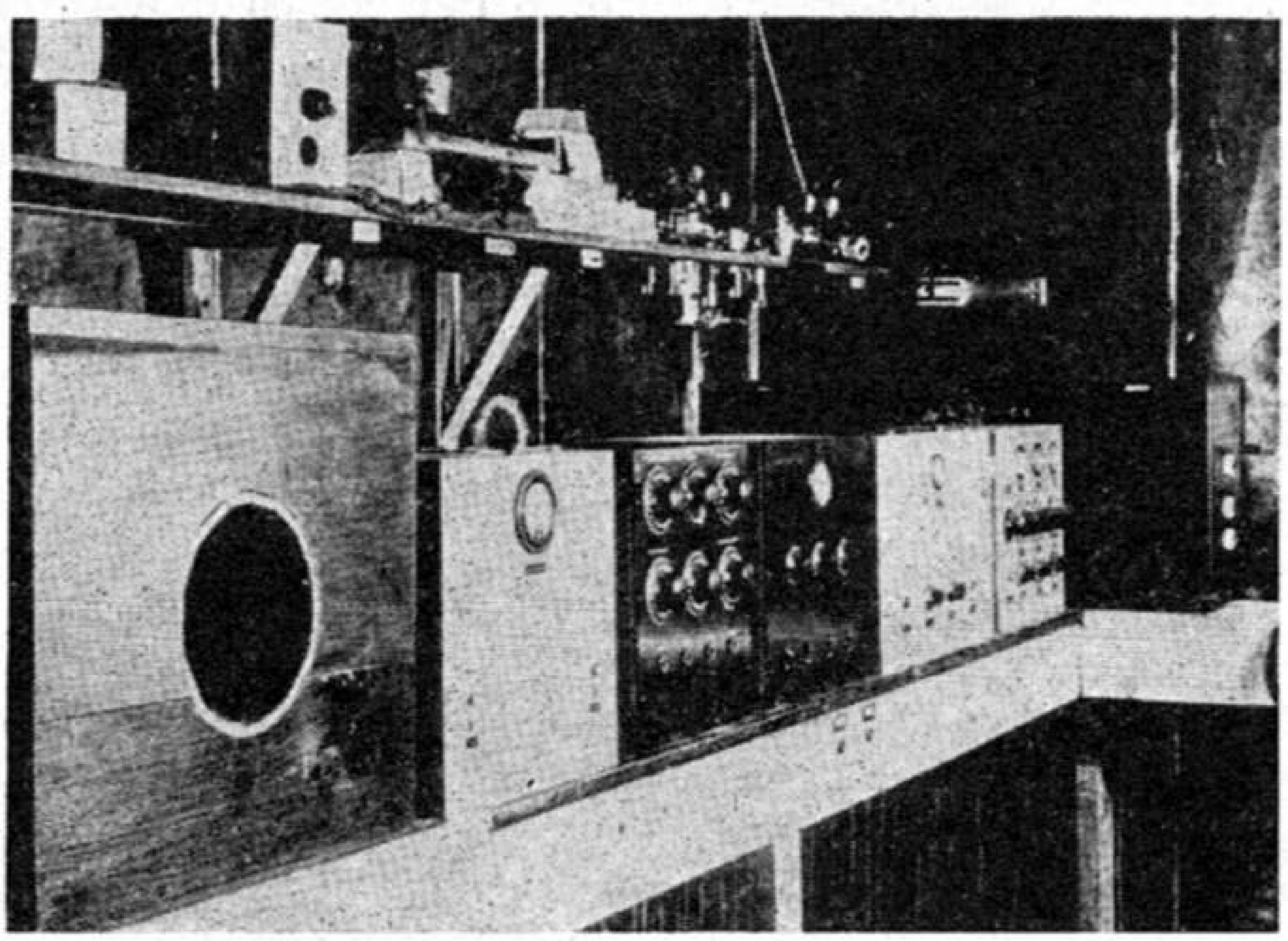

Fig. 21—Rocky Point receiving equipment for 200- to 500-megacycle signals.

After preliminary local tests, communication between Rocky Point and Riverhead, a distance of fourteen miles, was established. The 6-watt, 462-megacycle Barkhausen transmitter shown in Figures 11, 12, and 13 was used. This equipment was duplicated so that two-way telephony could be carried on. The Rocky Point receiving equipment is shown in Figures 21 and 22. Both transmitting and receiving antennas, which were of the billboard type shown in Figure 20, were mounted on supports fifty to seventy-five feet high in order to be in line of sight. As is usual when there is line of sight between transmitting and receiving antennas, no fading was observed. Rain, snow, and dense clouds of smoke from forest fires seemed to have no effect on the signals. The absence of fading on this circuit was a desirable

[6] B. Trevor and R. George, "Notes on Propagation at a Wavelength of Seventy-Three Centimeters," *Proc. I.R.E.*, Vol. 23, pp. 461-470; May, (1935).

feature since its purpose was to test the stability of transmitters and receivers. The equipment was used later for propagation studies under more difficult space-circuit conditions.

The Barkhausen transmitter, at Rocky Point, Figures 11, 12, and 13, was eventually replaced by a frequency multiplier unit, Figures 14, 15, and 16, capable of delivering up to 15 watts at 432 megacycles. The Rocky Point-Barkhausen and low power multiplier set-up is shown in

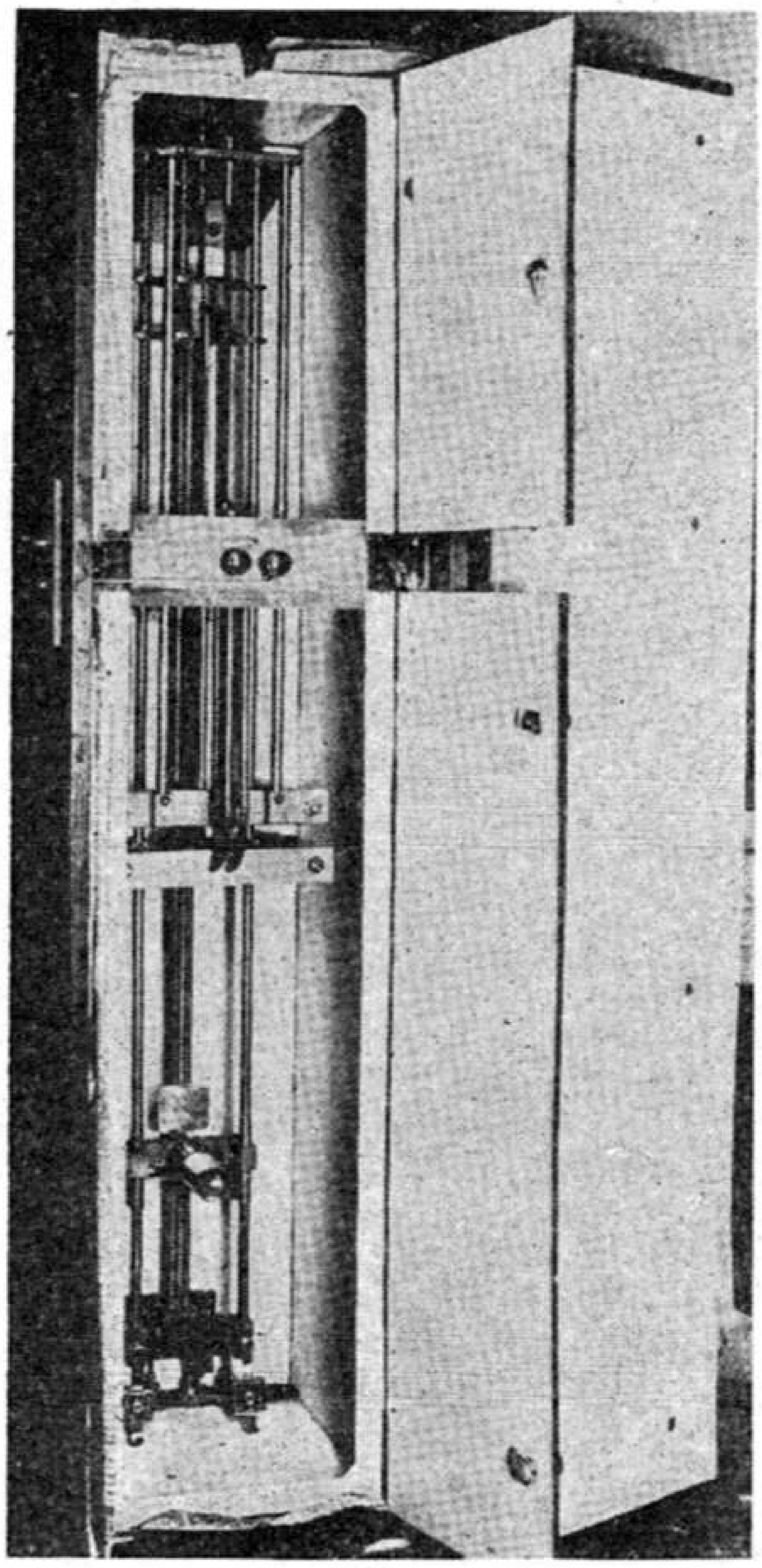

Fig. 22—Triode pendulum detector with trombone tuning circuits. Detail of unit in the background of Fig. 21.

Figure 23. Two horizontal V antennas were also erected. They were both seventy feet above the ground. One was 70 waves long and directed eastward on Riverhead. The other was 100 waves long and directed westward on the Empire State Building in New York City, fifty-six miles away. Signals from these antennas were observed with a portable receiver and a small directive antenna mounted on top of a car. Signals without fading were received at distances up to thirty

miles, in many localities considerably below the line of sight. By locating the receiving system on top of high buildings in New York and in airplanes it was found that signals without fading could be received at distances of from fifty to sixty miles when received as much as 500 feet below the line of sight. The distances below the line of sight given here represent actual values taken from contour maps of the terrain between transmitter and receiver. They will, therefore, check only approximately with simple geometric considerations based on the average curvature of the earth.

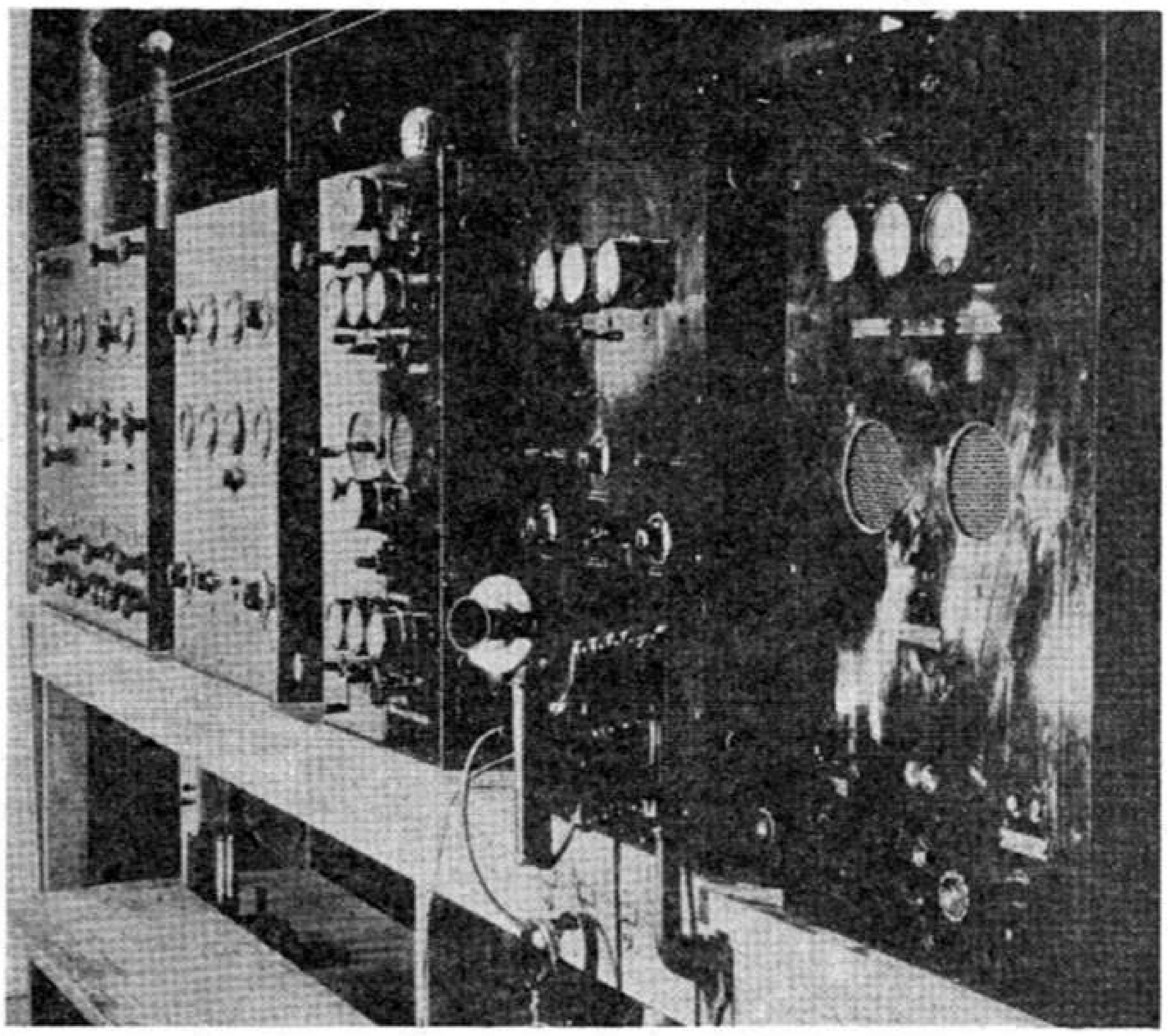

Fig. 23—Rocky Point low power ultra-high-frequency transmitter set-up. From left to right: 15-watt, 432-megacycle frequency multiplier; voltage regulator; 6-watt, 462-megacycle transmitter; compound modulator; and rectifier for modulator.

During these cruises with car and airplane, the unusual fact was observed that the apparent width of the beam was considerably smaller than the calculated width. For example, the beam from the 100-wave V antenna, which should have been about five miles wide over New York, seemed to be only two miles wide at the most.

After the 100-watt frequency multiplier transmitter became available it became possible to increase the range of observation. The frequency used was 411 megacycles. For the approximate distance of sixty miles, signals at ground level, 2000-3000 feet below the line of sight, would fade when completing their last lap over a very variable land and water route. When the receiving end of the route was over an uninterrupted body of water, there was very little fading at the time of observation. At a point 113 miles away, with only a relatively small stretch of water midway, only violently fading signals could be observed, even during prolonged observation periods. These observations were made at an elevation of about 400-500 feet above sea level and 8000 feet below the line of sight. It was also determined, that at least for this particular space circuit, horizontally polarized waves were considerably superior to vertically polarized waves. The fact was also observed that the plane of polarization at the receiver was at all times identical with that at the transmitter.

With the transmitting antenna 70 feet above the surrounding country and 170 feet above sea level, badly fading signals were observed in an airplane, 165 miles away, flying at a height of 7500 feet. In a later flight, after the height of the transmitting antenna had been increased to 120 feet above the surrounding country and after the receiver and the ignition system of the plane had been very substantially improved, surprisingly little distance was added to that obtained in the previous flight. Badly fading signals could still be observed at a distance of 172 miles when flying at an altitude of 7500 feet and two miles below the line of sight. The routes of these signals were chiefly over land.

It appears from these tests that the distance of reliable as well as unreliable signals increases with the increase of power at the transmitter. It is unsafe to predict whether this proportionality will remain when still higher powers are applied. The distance beyond line of sight, for reliable signals, will, of course, also depend upon the nature of the route.

If improved facilities result in much greater distances, no doubt the electrical conditions of the portions of space more remote from the earth's surface will play an important part in determining the propagation characteristics. The indications are that, at the present, most of the phenomena observed are obtained in the region of space near the earth's surface. No doubt such phenomena as nonuniform humidity and the surface condition of water bodies have a great influence upon the characteristics of the propagation along the earth's surface. The shape and nature of the landscape, needless to say, has an enormous influence.

In Table I, a chart of propagation results, obtained at different frequencies by various investigators, is shown. In comparing these results the method referred to by Jouaust[7] has been used. A factor m is used by which the radius of curvature of the earth must be multiplied to give the curvature of the propagation path. Thus if m assumes its smallest value, that of unity, the curvature of the propagation path

[7] R. Jouaust, "Some Details Relative to Propagation of Very Short Waves," *Proc. I.R.E.*, Vol. 19, pp. 479-489; March, (1931).

TABLE I

EXAMPLES OF ULTRA SHORT-WAVE TRANSMISSION

Frequency Megacycles	Wavelength Centimeters	Distance km	Distance miles	Elevation Meters *a*	Elevation Meters *b*	Value of *m*	Terminals of Test Circuit	Investigators
60	500	205	128	700	530	3.87	Nice-Corsica	Jouaust, Ferriè Milan
40	750	456	284	1462	0	1.1	Hawaii-Kauai	Beverage, Hansell
40	750	145	90	518	0	1.446	Kauai-Oahu	Peterson, Fifield, Matthews
44 61	682 492	446	278	1916	387	1.32	Empire State Building—Mt. Washington	Jones
527	57	270	168	750	340	1.58	Rocca di Papa—Cape Figari	Marconi, Mathieu
527	57	85	53	750	0	—3.0	Rocca di Papa—Yacht Elettra	"
480	70	90	56	304	51	2	Rocky Point—Empire State Building	Lindenblad, Dow, George, Trevor
411	73	96.5	60	52	18	1.22	Rocky Point—Montauk Point	"
406	74	180	112	70	116	1.16	Rocky Point—Arney's Mount	"
406	74	105	65	70	65	1.43	Rocky Point—Atlantic Highlands	"
406	74	274	170	70	2287	1.88	Rocky Point—Airplane	"

will be equal to the curvature of the earth. According to Humphrey the value of *m* for light is 5.7. Others have given it values as high as 10. The results given in the table may be judged by the smallness of the factor *m*. It can be seen that for frequencies above 30 megacycles, the Hawaii-Kauai telephone circuit has a very highly curved propagation path. At frequencies above 300 megacycles, very high curving was obtained on the test circuit between Rocky Point and Arney's Mount.

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