A NOVEL TYPE OF HIGH POWER PULSE TRANSMITTER

By K. LANDECKER* and K. S. IMRIE*

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Summary

A system of generation of radio waves is described which makes use of a symmetrical circular array of condensers charged through resistors and discharged through spark gaps in the manner of the Marx impulse generator. It is shown that exponential wave-trains of very high peak powers, of the order of 10,000 MW, may be radiated. The radiation resistance and radiation field of the structure are given and modification of the field pattern by parasitic elements is considered. Formulae and graphical aids are given which facilitate the design of such transmitters and experiments with various model transmitters are described. Consideration is given to circuit losses, particularly spark losses, and means are described to minimize these losses.

I. INTRODUCTION

In recent years a demand for high power pulses of radio-frequency waves has arisen in various branches of physics, as for example in ionospheric and cosmic research as well as in radio direction-finding, radar, and communication. However, the generation of large radio-frequency pulses by means of conventional transmitters is at present limited to peak powers of the order of 1 MW. Transmitters for powers much in excess of this limit would become prohibitively costly. The rapidly increasing difficulty in the construction of large pulse transmitters is not only governed by the increase in the size and cost of the constructional elements, that is, the transmitting valves and their associated circuits, the aerial system, and the coupling elements between the transmitter and the aerial system, but also by the fact that new phenomena come into play which are not present in transmitters designed for moderate powers. We here merely point out one particular difficulty, namely, the power loss from corona discharges in the atmosphere surrounding the aerial system.

The purpose of the present paper is to report on the results of experiments with various models of a novel type of pulse transmitter, which indicate that it is quite feasible to generate pulses of a peak power of the order of 10 000 MW at a small fraction of the cost of a corresponding conventional transmitter. In addition we shall refer below (in Section VI) to certain aspects of this principle of wave generation which appear to indicate that there exists a fundamental upper limit to the maximum power that, with materials available at present, may be radiated from a point in space.

II. DESCRIPTION OF THE PRINCIPLE OF TRANSMISSION

The principle of transmission may be conveniently explained with the aid of the schematic diagram Figure 1. A number of sets of electrical components $\overline{L}$, $\overline{C}$, $\overline{R}$, and S are shown arranged in circular form. The eight capacitors $\overline{C}$

* Department of Physics, The University of New England, Armidale, N.S.W.

are representative of an arbitrarily large number of condensers whose series combination forms the tuning capacity, while the corresponding tuning inductances $\bar{L}$ are located symmetrically with respect to the condensers and spark gaps S and may, at higher frequencies, be formed solely by the connecting leads. In a limiting case they may even degenerate into the internal inductances of the condensers. The total tuning inductance is then the inductance of the circular current path through the condensers and spark gaps, and it will presently become clear that this is the desirable condition for maximum energy storage.

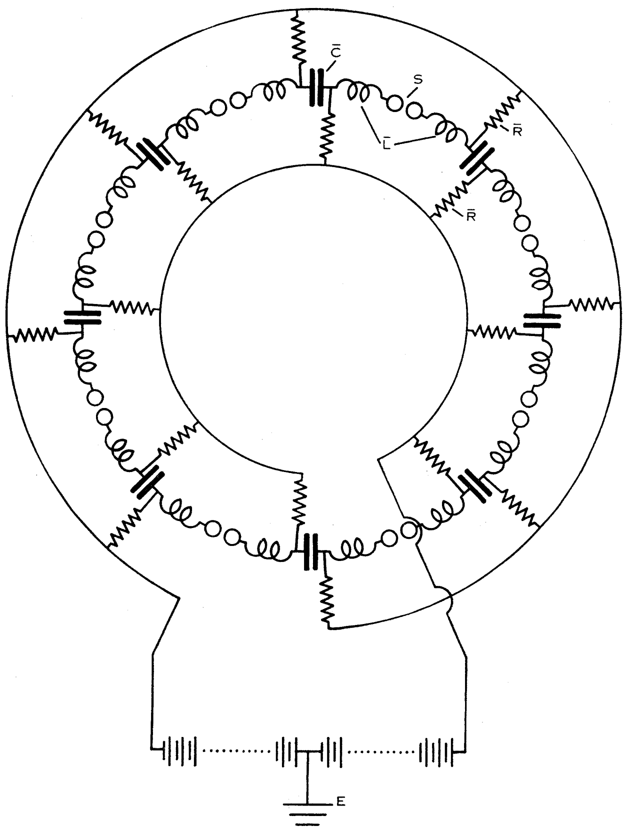

Fig. 1.—Schematic circuit diagram of the transmitter.

The condensers $\bar{C}$ are charged in parallel through the resistors $\bar{R}$ and discharged in series through the spark gaps S in the manner of the well-known Marx impulse generator (Edwards, Husbands, and Perry 1951; Craggs and Meek 1954). However, the structure described forms not only the tank circuit of the transmitter but also is extended spatially so as to form at the same time a magnetic dipole or loop aerial which itself radiates the radio-frequency energy. A variation of this principle using parasitic elements in addition to the main oscillatory circuit will be referred to below.

Anticipating the results of calculations and experiments quoted below, which show that this system of transmission may be made to function and that very large power pulses may in fact be radiated, we enumerate some advantageous properties of this scheme:

1. The energy stored in the tuning condensers is transformed into radiation in a most direct manner. This outweighs the fact that higher electrical energies may possibly be stored in unit volume by other means, for example by homopolar generators and the like, than it is possible to store in condensers with present-day dielectric materials.

2. In the presence of an atmosphere a magnetic dipole is inherently superior as a radiator to an electric dipole. A magnetic dipole fails at high power because it ultimately gives rise to an electrodeless discharge in the surrounding air. An electric dipole causes a corona discharge at the field boundaries (the " ends " of the aerial wire) long before an electrodeless discharge can be initiated. The circular array of condensers of Figure 1 approaches a perfect magnetic dipole as the number of condensers is increased and their individual capacities increased simultaneously beyond all limits in such a way that the LC product of the entire circuit remains at a constant desired value. In practice it is sufficient to subdivide the condenser bank to such an extent that the individual condensers are able to withstand their charging potentials. The latter are the only scalar potentials that arise in the circuit. This statement is related to a well-known electrodynamic theorem which has been frequently mentioned in the literature (Howe 1945) and according to which no scalar potential difference exists between any two points of a conducting annulus situated in a varying magnetic field of axial symmetry. Experience indicates that with slight departures from a perfectly circular form and from perfect symmetry there is still little tendency for a corona discharge or flashover to occur.

3. Since no point of the structure is necessarily at ground potential, it is possible to ground the electrical centre of the voltage supply. The latter therefore need only be insulated for one-half of the condenser charging voltage.

III. Calculation of the Power of the Emitted Wave-train

The stored energy will be radiated in the form of exponentially decaying wave-trains. To obtain an estimate of the power that such a system is capable of radiating we begin by calculating three characteristic quantities of the emitted wave-train: the average power during the first half cycle, the peak power of the entire wave-train which occurs instantaneously at the current maximum of the first half cycle, and the approximate average power of the total wave-train.

Assuming that N condensers each of capacity $\overline{C}$ are distributed around the circumference of the circuit, and that they are designed to withstand a maximum charging voltage V, the total energy E_{tot} stored in the condenser bank is related to the current in the circuit through

$$E_{\text{tot}}=\tfrac{1}{2}N\overline{C}V^2=\int_0^\infty I_0^2 \sin^2 \omega t \, \mathrm{e}^{-2kt}R\,\mathrm{d}t, \qquad \ldots\ldots\ldots (1)$$

where $k=R/2L$, L is the circuit inductance, $\omega=(N/L\bar{C}-R^2/4L^2)^{\frac{1}{2}}$, R is a resistance representing radiation and circuit losses, and I_0 is the current in the circuit in the absence of damping ($R\rightarrow 0$).

From equation (**1**) we obtain

$$\frac{N\bar{C}V^2}{I_0^2R}=\int_0^\infty \mathrm{e}^{-2kt}(1-\cos 2\omega t)\mathrm{d}t$$

$$=\left[\frac{\mathrm{e}^{-2kt}}{-2k}\right]_0^\infty-\int_0^\infty \mathrm{e}^{-2kt}\cos 2\omega t\ \mathrm{d}t$$

$$=\frac{1}{2k}-\int_0^\infty \mathrm{e}^{-2kt}\cos 2\omega t\ \mathrm{d}t, \qquad \textbf{(2)}$$

and, integrating the second term by parts,

$$\frac{N\bar{C}V^2}{I_0^2R}=\frac{1}{2k}-\frac{k}{2\omega^2}+\int_0^\infty \frac{k^2}{\omega^2}\mathrm{e}^{-2kt}\cos 2\omega t\ \mathrm{d}t. \qquad \textbf{(3)}$$

On multiplying (**2**) by k^2/ω^2 and adding to (**3**) there results

$$\frac{N\bar{C}V^2}{I_0^2R}\left(\frac{k^2}{\omega^2}+1\right)=\frac{1}{2k}, \qquad \textbf{(4)}$$

from which follows

$$I_0=NV/\omega L, \qquad \textbf{(5)}$$

and therefore the average power during the first half cycle is closely

$$P_{0\,(\mathrm{av})}=\tfrac{1}{2}I_0^2R=\tfrac{1}{2}R(NV/\omega L)^2. \qquad \textbf{(6)}$$

In all cases of practical interest $\omega\approx(N/L\bar{C})^{\frac{1}{2}}$, that is, $\omega L\approx N/\omega\bar{C}$. Introducing the Q-factor of the circuit $Q=\omega L/R=N/\omega\bar{C}R$, the average power during the first half cycle may also be expressed as

$$P_{0\,(\mathrm{av})}=\tfrac{1}{2}N\bar{C}V^2\omega/Q=E_{\mathrm{tot}}\omega/Q \text{ watts}, \qquad \textbf{(7)}^*$$

when $\bar{C}$ is given in farads, V in volts, and E_{tot} in joules. The instantaneous peak power at the first current maximum is double this value, that is,

$$P_{0\,(\mathrm{peak})}=2E_{\mathrm{tot}}\omega/Q \text{ watts}. \qquad \textbf{(8)}$$

Lastly, in order to determine the approximate average power during one wave-train, we assume that the wave-train may be considered as terminated when the current amplitude has decreased to 1 per cent. of its initial value (Fleming 1919). Under these conditions the duration τ of the wave-train is given by

$$\left.\begin{aligned} &\mathrm{e}^{-k\tau}=0\cdot 01,\\ \text{or}\qquad &-k\tau=\ln 0\cdot 01=-4\cdot 6,\end{aligned}\right\} \qquad \textbf{(9)}$$

* The same expression for $P_{0\,(\mathrm{av})}$ (except for a factor $(1-\mathrm{e}^{-\delta/2})$ not very much different from unity) is obtained by considering the wave-train to consist of a succession of half sinoids of amplitudes $I_0, I_1, I_2, \ldots$, where successive amplitudes are related by the logarithmic decrement $\delta=\pi/Q$ through $I_0/I_1=I_1/I_2=I_2/I_3=\ldots=\mathrm{e}^{\delta/2}$.

but, since

$$k = R/2L = \omega/2Q, \quad \ldots\ldots \quad (\mathbf{10})$$

we obtain for the duration of the train the value

$$\tau = 4 \cdot 6/k = 4 \cdot 6 \times 2Q/\omega = 9 \cdot 2Q/\omega \sim 10Q/\omega \text{ seconds.} \quad \ldots \quad (\mathbf{11})$$

The average power of the whole train is therefore given with sufficient accuracy by

$$P_{\text{tr (av)}} = \tfrac{1}{2} N \bar{C} V^2 \omega / 10Q = E_{\text{tot}} \omega / 10Q \text{ watts.} \quad \ldots\ldots \quad (\mathbf{12})$$

Finally we note that from (**11**) there follows the useful expression for the number of cycles in the train

$$n = \omega\tau/2\pi = 9 \cdot 2Q/2\pi = 1 \cdot 46Q \sim 1 \cdot 5Q. \quad \ldots\ldots \quad (\mathbf{13})$$

It is necessary to show that it is sufficiently accurate to include the radiation resistance in the total circuit resistance R of equation (**1**) as a part that is independent of frequency.

So far in this discussion we have assumed that the wave-trains are generated in the manner described in Section II, without going into the process of transmission in detail. This process depends fundamentally on the Fourier composition of the train. Fortunately, the frequency composition of an exponentially decaying wave-train may be stated in very simple terms. It is well known that the Fourier transform of such a train is identical with the frequency response of a tuned *LRC* circuit.* However, the radiation resistance of a transmitting aerial is a function of frequency and also a function, unfortunately not at all simple, of the spatial configuration of the aerial. The general problem of transmission and reception of arbitrary wave shapes is in fact exceedingly difficult. However, it will be shown in the following section that, though the radiation resistance of a circular loop exhibits a general increase with diameter but oscillates for large diameters, it nevertheless shows a simple monotonic increase within the range of interest (see Fig. 2). For all loop diameters which are practical the radiation resistance increases approximately with the fourth power of the diameter (see Fig. 3). From the foregoing it follows that it is permissible to assume that the frequency components of the radiation field have appreciable values only in the neighbourhood of the frequency of oscillation of the wave-train, provided that the train is not too short. It has in fact always been found that under these conditions the radiation field of a spark transmitter is a time function closely similar to the aerial current. The circumstance that in reality, in the process of radiation from our transmitting loop, the higher frequency components are always favoured compared to the lower frequency components, makes the above assumption of minor importance in practice, but this simplification greatly reduces the complexity of the problem.

* See, for example, the Fourier pairs Nos. 448 and 449 in Campbell and Foster (1931).

Finally, it should be noted from equations (7), (8), and (12) that the power of the wave-train is simply inversely proportional to the Q-factor of the circuit, which is solely determined by radiation and circuit losses. It will be shown in the following that the circuit may always be adjusted so that the radiation losses may have any desired value, and that the circuit losses may be minimized by various means. The question of which particular value of the Q-factor is desirable will largely depend on the specific application of the emitted energy. For example, the wave shape most suitable for producing changes in an ionized medium will not be the same as that of a signal to be received against a strong background of noise. In transmitting practice it is accepted that the loaded Q of a transmitter should be at least 10 in order to ensure that the major part of the wave energy is radiated near the fundamental frequency. It can only be estimated that in general the choice of the factor will range between values of 10 and 50, and in the following we shall consider numerical examples in this range only.

IV. The Radiation Resistance of the Circuit

In the previous section the significance of the Q-factor was emphasized. It is therefore of importance to determine what fraction of the total damping resistance is made up of undesirable circuit losses. As will be shown below, the major portion of these losses is accounted for by losses in the sparks and means will be mentioned to minimize these losses. In order to render the problem manageable we therefore initially disregard the circuit losses and deal first with the radiation resistance.

It is not immediately obvious that when a desired frequency of transmission and a maximum condenser voltage are specified the circuit constants may be made to converge towards values which are practicable and which ensure a large output of radiated power. The frequency fixes in the first instance the LC product in which the factor C should ideally be obtained from the largest number of series capacities it is possible to accommodate along the circumference of the circuit, allowing sufficient space for the spark gaps. The factor L, on the other hand, is a function of the diameter of the circuit and depends only weakly on the average cross section of the current path. The diameter of the circuit, however, also determines the radiation resistance but, as mentioned in Section III, the latter unfortunately is not a simple function of the former. If a suitable radiation resistance (a suitable Q-factor) is chosen, then the loop diameter, the tuning inductance, and the tuning capacity are determined. The number (N) of condensers is limited by space requirements and it might well have been that the energy stored in the condenser bank and therefore also the radiated power were small. That the power is in fact large can only be shown by numerical examples or by the dimensional reasoning adopted in Section VI.

The radiation resistance of circular current loops whose diameter is an appreciable fraction of a wavelength has been calculated by various authors (Foster 1944 ; Moullin 1946) and, in addition, the field distribution around such loops has also been worked out.

The radiation resistance is given by

$$R^*=\tfrac{1}{2}\pi\mu_0 ck\int_0^{2k} J_2(x)\mathrm{d}x \text{ ohms}, \qquad \text{(14)}$$

where $\mu_0=1\cdot 26\times 10^{-6}$ henry/m, c=velocity of light$=3\times 10^8$ m/sec, $k=2\pi a/\lambda$, a=radius of loop, λ=wavelength, and $\mathbf{J}_2(x)$ is the Bessel function of the first kind and second order (Fig. 2).

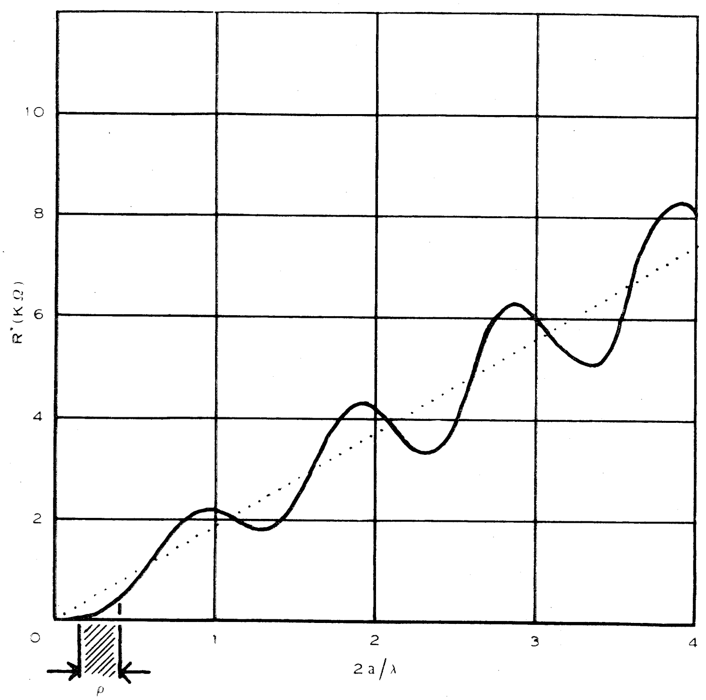

Fig. 2.—The radiation resistance of a circular loop as a function of its diameter (in wavelengths). ρ indicates the region of interest (see text).

This may also be written in the form of a power series in k as

$$R^*=20\pi^2k^4\left(1-\frac{k^2}{5}+\frac{k^4}{56}-\ldots\right), \qquad \text{(14a)}$$

which shows that the radiation resistance of a loop which is small compared to the wavelength approximates to

$$R^*=20\pi^2k^4=320\pi^6(a/\lambda)^4. \qquad \text{(14b)}$$

Equation (**14b**) still holds within 20 per cent. up to a value of $k=1$. Using the three terms of the power series in (**14a**) gives R^* within a few per cent. at $k=1$.

From equation (**14**) the radiation resistance R^* of the loop has been plotted as function of the diameter in wavelengths in Figure 3 over the range which will be shown to be of interest to us.

The inductance L of the circular loop which together with the resistance R^* of equations (**14**), (**14a**), or (**14b**) enters the Q-factor is given by

$$L = \mu_0 a\{\ln(8a/b) - 1\cdot 75\}, \quad \ldots\ldots\ldots\ldots\ldots \quad (\mathbf{15})$$

where a=loop radius, as before, and b=(average) radius of the cross section of the current path.

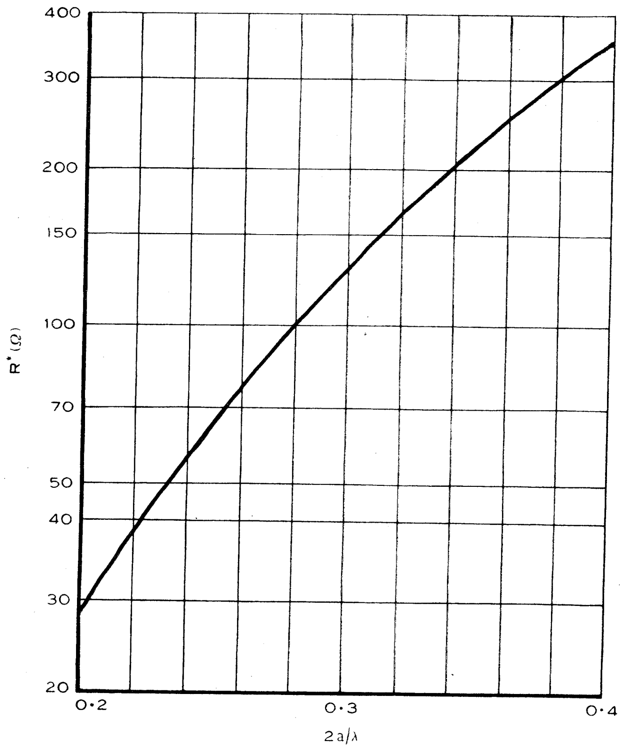

Fig. 3.—The radiation resistance of the loop within the range of interest (see text).

Since the ratio a/b and therefore also the term $\ln(8a/b)$ are restricted by practical considerations to a range with rather definite limits the inductance may be written in an approximate form

$$L \approx D\mu_0 a, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (\mathbf{15a}).$$

where D is a constant.

Since the loop radius a enters equations (**14b**) and (**15a**) through the fourth and first power respectively it follows that a desired Q-factor may always be realized. Using (**14**) and (**15**) the Q-factor may be written

$$Q = \left\{\frac{2}{\pi}\left(\ln\frac{8a}{b} - 1\cdot 75\right)\right\}\left\{\int_0^{2k} J_2(x)\mathrm{d}x\right\}^{-1}. \quad \ldots\ldots \quad (\mathbf{16})$$

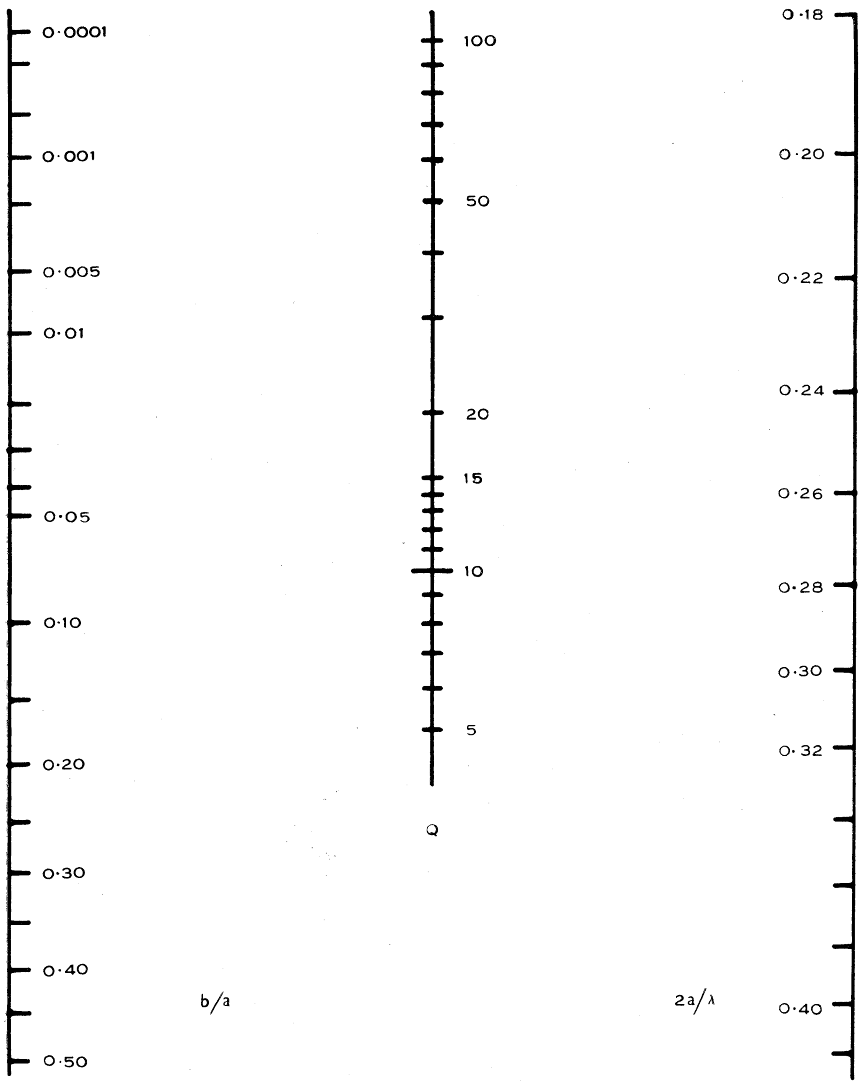

Fig. 4.—Nomogram relating the circuit diameter as a fraction of the loop diameter, the Q-factor, and the loop diameter in wavelengths.

This equation may be put into the form

$$\log Q = \log f(b/a) + \log g(2a/\lambda), \quad \ldots\ldots\ldots\ldots \quad \textbf{(16a)}$$

where f and g are functions following from (**16**), and therefore a nomogram of Q, b/a, and $2a/\lambda$ may be constructed as shown in Figure 4. The nomogram shows at a glance that practical loop diameters will mainly be restricted to the range from $0 \cdot 2\lambda$ to $0 \cdot 3\lambda$.

V. The Radiation Field of the Loop and the Effect of Parasitic Elements

The electric and magnetic vectors of field strength E and B, at a distance r from the centre of a circular loop of radius a, have the following magnitudes (Foster 1944; Moullin 1946)

$$E = \tfrac{1}{2}\mu_0 c I_a k \mathrm{J}_1(k \cos\varphi)\cdot\frac{1}{r}\sin\left(\omega t - \frac{\omega r}{c}\right), \quad \ldots\ldots\ldots (17)$$

and

$$B = -\tfrac{1}{2}\mu_0 I_a k \mathrm{J}_1(k \cos\varphi)\cdot\frac{1}{r}\sin\left(\omega t - \frac{\omega r}{c}\right), \quad \ldots\ldots (18)$$

where I_a is the amplitude of the current in the loop, $r \gg a$, φ is the angle between the plane of the loop and the radius vector to the reference point, $\mathrm{J}_1(x)$ is the Bessel function of the first kind and first order, and the other symbols have the same meaning as before.

With the plane of the loop considered as an equatorial plane, the electric vector oscillates tangentially to a circle of latitude and the magnetic vector tangentially to a meridian. This should be noted when comparing the radiation field of the loop with that of an electric dipole.

When the diameter of the loop is much smaller than a wavelength, that is, when $k \ll 1$, these expressions approximate to

$$E = \tfrac{1}{4}\mu_0 c I_a k^2 \cos\varphi\cdot\frac{1}{r}\sin\left(\omega t - \frac{\omega r}{c}\right), \quad \ldots\ldots\ldots (19)$$

$$B = -\tfrac{1}{4}\mu_0 I_a k^2 \cos\varphi\cdot\frac{1}{r}\sin\left(\omega t - \frac{\omega r}{c}\right). \quad \ldots\ldots\ldots (20)$$

These approximations are correct to within about 10 per cent. even up to $k=1$, so that even when the loop is one wavelength in circumference the radiation field is still very like that of a small magnetic dipole. For reasons stated in Section IV this will nearly always be so for the transmitting loop we are considering.

It should be noted that, whenever the Bessel function $\mathrm{J}_1(x)$ passes through zero, extinction angles occur near the equatorial plane and progress towards the zenith with increasing radius of the loop until the entire quadrant is divided into lobes. The first zero of the Bessel function occurs for the argument $x=3\cdot83$, that is, an extinction angle occurs for the first time when $x=2\pi a/\lambda=3\cdot83$ or $2a/\lambda=3\cdot83/\pi=1\cdot22$. But since we are here always restricted to the condition $0\cdot2<2a/\lambda<0\cdot3$ this means that we have always only a single lobe.

There are various possibilities of arranging parasitic elements (reflectors and directors) in the neighbourhood of the main loop for the purpose of modifying the radiation pattern. Some of these are shown schematically in Figure 5.* C represents a biconical reflector suggested by Moullin (1946) and D represents

* Various configurations like the closed coplanar rings A and coaxial rings B call to mind various electric counterparts, such as broadside, endfire, Yagi array, etc., but it is doubtful whether any useful inferences may be made from these analogies.

a parabolic reflector. It is to be noted that all axially symmetrical elements such as A and B share the property with the main circuit that no scalar potential arises between any two points of the circumference.

The question whether it is possible to induce sufficient current into any of these parasitic elements and still effect a worth-while modification of the polar pattern by placing the element at a suitable distance is in general difficult to analyse and is best decided by experiment. The tuned secondary circuit mentioned in Section VII will also affect the radiation pattern to some extent and a choice may have to be made regarding its position with respect to the main circuit and whether more than one secondary circuit should be used.

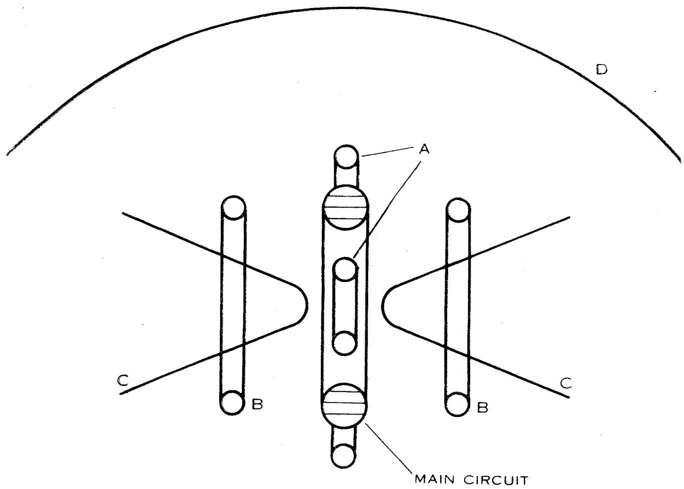

Fig. 5.—Various forms of parasitic elements used in conjunction with the main driving circuit.

VI. Numerical Examples. Some Considerations regarding the Maximum Amount of Wave Power that may be produced in Space

We now turn to some numerical examples and assume to begin with that a wave of a frequency of 1 Mc/s is to be produced and that the condensers will be designed to withstand a charging voltage of $V=200$ kV. Condensers for such a voltage may today be considered to be standard items in engineering practice. The Q-factor will be taken to be 10, and initially we shall ignore circuit losses. Selecting a value of (diameter of loop)/(wavelength) of $0\cdot 28$, the nomogram (Fig. 4) gives a diameter of the current path of $0\cdot 06$ of the loop diameter and we see that a circular structure of 80 m diameter and a cross section of the current path of $4\cdot 8$ m diameter is required. This would call for large tubular condensers with air or possibly polythene ribbon as a dielectric. The loop will have an inductance of $L=170$ μH and therefore requires a tuning capacity of $\overline{C}/N=1\cdot 5\times 10^{-4}$ μF. We now suppose that $N=50$ condensers are distributed around the circumference, that is, that ~ 5 m of circumference are available for each condenser and its associated spark gap, though a design as shown schematically in Figures 6 (a) and 6 (b) would allow us to accommodate many more units around the circumference, even when the spark gaps are operated at atmospheric pressure. The capacity of each of the 50 units is then $\bar{C}=50\times1\cdot5\times10^{-4}=7\cdot5\times10^{-3}$ μF, and the capacity of the whole condenser bank $N\bar{C}=50^2\times1\cdot5\times10^{-4}=3\cdot75\times10^{-1}=0\cdot375$ μF. The energy stored in the total capacity is given by

$$E_{\text{tot}}=\tfrac{1}{2}N\bar{C}V^2=0\cdot5\times0\cdot375\times10^{-6}\times(2\times10^5)^2=7\cdot5\times10^3\ \text{J}.$$

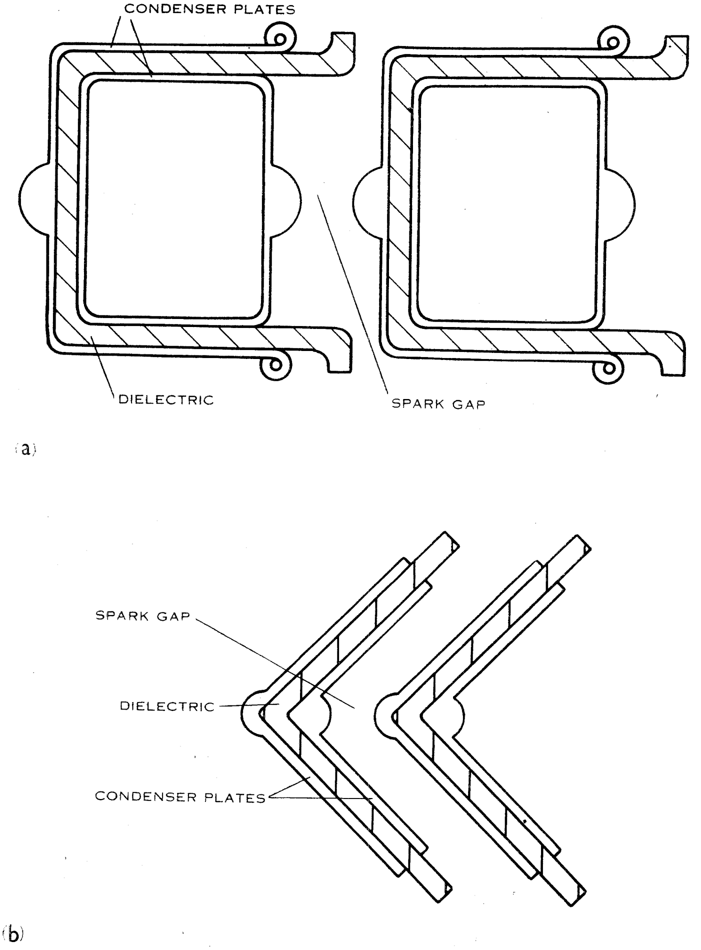

Fig. 6.—Schematic diagram of space-saving arrangement of condensers.

We then obtain from equations (**7**), (**8**), and (**12**) of Section III :
Average power during the first half cycle

$$P_{0\,(\text{av})}=7\cdot5\times10^3\times6\cdot28\times10^6/10=4\cdot7\times10^9\ \text{J/sec}$$
$$=4700\ \text{MW}.$$

Peak power at first current maximum

$$P_{0\,(\text{peak})}=2P_{0\,(\text{av})}=9400\ \text{MW}.$$

Average power during the wave train

$$P_{\mathrm{tr\,(av)}}=P_{0\,\mathrm{(av)}}/10=470\ \mathrm{MW},$$

and equation (**13**) shows that the train lasts for $n=1\cdot 5Q=15$ cycles.

This example shows that it is quite feasible to obtain with this arrangement and a condenser voltage slightly larger than 200 kV peak powers of the order of 10 000 MW. The structure is, however, very large, even if it should be possible the reduce the dimensions by improvements in design and judicious use of parasitic elements, as discussed in Section V. Nevertheless, it covers no more ground than a conventional aerial array at this frequency. If used for ionospheric work it might be advantageous to erect the transmitter at or near the bottom of a natural valley in order to direct the radiation upwards.

We next consider a more readily realizable example and assume a desired frequency of 30 Mc/s, a maximum condenser voltage of 200 kV, and a Q-factor of 15. Proceeding as before, we select from the nomogram a loop diameter of $2\cdot 8$ m, which fixes the diameter of the current path at about 4 cm and its inductance at $L=16\ \mu$H. This requires a tuning capacity of $\overline{C}/N=1\cdot 75\ \mu\mu$F. Accommodating $N=40$ condensers around the circumference allows 22 cm for the space to be occupied by one condenser and its associated spark gap, which is ample. Proceeding as in the previous example we obtain :

$$\begin{aligned}
\overline{C}&=40\times 1\cdot 75\times 10^{-12}=70\ \mu\mu\mathrm{F},\\
N\overline{C}&=2800\ \mu\mu\mathrm{F},\\
E_{\mathrm{tot}}&=\tfrac{1}{2}\times 2800\times 10^{-12}(2\times 10^{5})^{2}=56\ \mathrm{J},\\
P_{0\,\mathrm{(av)}}&=56\times 6\cdot 28\times 30\times 10^{6}/15=700\ \mathrm{MW},\\
P_{0\,\mathrm{(peak)}}&=2\times \mathrm{P}_{0\,\mathrm{(av)}}=1400\ \mathrm{MW},\\
P_{\mathrm{tr\,(av)}}&=P_{0\,\mathrm{(av)}}/10=70\ \mathrm{MW},\\
n&=1\cdot 5\times 15\approx 22\ \text{cycles}.
\end{aligned}$$

We again note that very large powers are radiated and yet the circuit is very easy to construct. This example was selected because a transmitter approximating to these specifications is at present being designed and constructed in this laboratory.

Finally, we consider the maximum peak power that it is possible to radiate with this type of transmitter. For this purpose it is convenient to rewrite equation (**8**) of Section III as follows

$$P_{0\,\mathrm{(peak)}}=(NV)^{2}/Q^{2}R\ \text{watts.} \qquad \text{(8a)}$$

We now assume that for the construction of the condensers a low-loss dielectric material with a breakdown strength of $\Delta=5\times 10^{7}$ V/m is available (this is about the breakdown strength of polystyrene), that one-quarter of the circumference of the transmitting loop is taken up by dielectric, and that the other three-quarters is occupied by the spark gaps and the condenser plates. It will be shown in Section VII that it is quite feasible to control the spark length by pressurization of the spark gaps and that the above allocation of space for the spark gaps is ample. The charging voltage of the condensers may be expressed as $V=\frac{1}{2}\pi a\Delta/N$ and, since it follows from the foregoing that in any practical design it is not possible to deviate much from the values $2a \sim 0 \cdot 29\lambda$, $Q \sim 10$, $R \sim 100\ \Omega$, equation (**8a**) becomes

$$P_{0\,(\text{peak})} = (\tfrac{1}{2}\pi a\Delta)^2/Q^2R = (\tfrac{1}{4}\pi \times 0 \cdot 29\lambda\Delta)^2/Q^2R$$
$$= (1 \cdot 2 \times 10^7\lambda)^2/10^4 = 10^{10}\lambda^2 \text{ watts.} \qquad \ldots\ldots\ldots (\mathbf{8b})$$

From (**8b**) it follows that it should be possible to produce peak powers of the order of 10^4, 10^6, and 10^8 MW at wavelengths of 1, 10, and 100 m respectively. Even when circuit losses are taken into account this calculation demonstrates that very large peak powers may be produced. Further, this result seems to us to have also a fundamental significance. Unless entirely new methods of radiating electrical energy from a point into space are discovered, equation (**8b**) may represent a limiting value for such radiation with present-day dielectric materials and insulating techniques.

VII. Experiments with Various Scale Models

In order to verify the feasibility of this principle of transmission and the calculations of the previous sections, experiments have been carried out with two transmitters. The first operated at a frequency of 10 Mc/s and used 6 tubular air-insulated condensers. The average loop diameter was about 2 m, that is, only 1/15 of a wavelength, and so the radiation resistance was very low. This transmitter was mounted in the open on a low wooden tower. It proved very difficult to protect it from the weather. A second transmitter was constructed working at a frequency of 70 Mc/s. It uses 18 parallel-plate condensers with a dielectric of polystyrene and 18 associated spark gaps. The mean loop diameter is approximately 1 m, which corresponds to a radiation resistance of about 100 Ω. This transmitter is small enough to be operated in the laboratory. Both transmitters must be considered to be scale models because the condensers in the 10 Mc/s transmitter are not able to withstand a charging voltage of more than 5 kV and those in the 70 Mc/s transmitter more than 15 kV. The charging resistances each had a value of 10 MΩ in both models. In addition to experiments with these transmitters, many observations were made on simple tuned circuits.

The results of these experiments may be summarized as follows :

(i) It was found that the spark gaps of the transmitters could be adjusted to fire quite regularly and strong signals were received at distances of many wavelengths from both transmitters. It was immediately established that the transmitting loops exhibited the radiation pattern of a dipole and that the field vectors had the correct orientations. The signal strength was of the expected order of magnitude, but experience with these model transmitters has shown that accurate measurement of the field strength of short, strongly damped, high frequency pulses presents a special problem, and various detectors are being designed for this purpose.

(ii) Near the transmitters the signals are easily displayed on the screen of a cathode-ray tube. Observations of the pulse length indicate that by far the largest part of the circuit losses is accounted for by spark losses, and various attempts were made to minimize these losses. The most effective means of controlling the pulse length proved to be the coupling of a tuned secondary circuit with the main driving circuit. This of course used to be standard practice in spark telegraphy, but with the arrangement we are considering the problems are somewhat different from those encountered in spark telegraphy. The tuned secondary takes the place of one of the untuned parasitic elements of type A or B in Figure 5 (Section V). The radiation resistance of such a passive element by itself will be either exactly or nearly exactly the same as that of the main circuit. If an untuned parasitic reflector is coupled to the main circuit it modifies the radiation pattern and also increases the radiation resistance of the whole combination.* A tuned secondary, on the other hand, in addition reduces the energy losses in the whole system because while being driven by the main circuit it abstracts oscillatory energy from this circuit and continues to radiate after the sparks are extinguished. It was found that such a tuned secondary controlled the pulse length very effectively. Experiments with single tuned circuits at a frequency of 10 Mc/s showed that the pulse length could be extended by this means by at least a factor of 10 without significantly affecting the peak amplitude. Maximum improvement occurs at slightly below optimum coupling. Finally, it should be noted that the tuned secondary circuit shares with the main circuit the property that no scalar potential differences appear between any two points of its circumference provided the tuning condensers are able to withstand the oscillating voltage.

The spark discharge was also studied at pressures higher than atmospheric and an adjustable spark gap was constructed which is capable of being pressurized up to 100 atmospheres. The most useful gas for this purpose proved to be nitrogen, in agreement with various statements in the literature. Replacing a spark gap working at atmospheric pressure in an oscillating circuit by a pressurized gap with the same breakdown voltage always increased the pulse length ; that is, no combination of circuit constants was found in which pressurization reduced the pulse length. The actual increase in pulse length depends very much on the circuit constants and may be as much as by a factor of 2. Such a factor is very desirable but the main advantage of pressurization for us seems to be the possibility of reducing the space requirements of the spark gaps and, incidentally, also the noise from the sparks. Moreover, a design shown schematically in Figure 7, which is quite feasible at frequencies above 10 Mc/s, would protect the circuit from humidity and dust and from the effects of high altitude. We are at present constructing a 35 Mc/s transmitter according to this design.

(iii) According to the calculations of Section IV the optimum diameter of the loop will practically always be within the limits of 0·2–0·3 of one wavelength, so that the firing impulse propagates from one spark gap to the next along the circumference in a finite time which is an appreciable fraction of a period. It was therefore anticipated that a separate firing impulse might have to be applied, by some means from the axis of the loop, so as to arrive simultaneously at all the spark gaps. However, it was noted from the beginning that the firing of

* Here and in the following the radiation resistance is referred to the driving current in the main circuit. Detuning of the main circuit due to the coupled reactance is of no practical importance.

all the gaps seemed to take place surprisingly decisively, though one could not be sure that the circuit did not support some unwanted mode along its circumference. This was tested, using the 70 Mc/s transmitter, by firing all gaps simultaneously by means of a flash of ultraviolet light from an auxiliary bright spark between aluminium electrodes situated at the centre of the loop. No significant difference in operation could be detected with and without the auxiliary spark. It therefore appears that the desired principal current mode established itself within a sufficiently short time by the mechanism that is responsible for the operation of the Marx impulse generator.

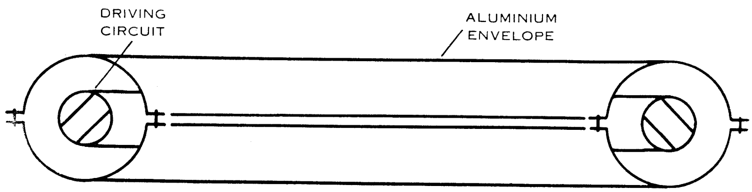

Fig. 7.—Schematic drawing of cast aluminium envelope for pressurization of the circuit.

VIII. Conclusion

Summarizing, we can state that theoretical and experimental work on this problem has at the time of writing reached a stage where the mode of operation and the limitations of this transmitter are well understood and the properties of a practical design may be predicted with sufficient accuracy. We are at present constructing a 60 ft diameter parabolic reflector for a 35 Mc/s transmitter with the aim of radiating pulses with a peak power of about 1000 MW for a programme of ionospheric and cosmic research.

In this work we have been led to numerous other problems whose investigation has had to be postponed. These include the possibility of using lengths of transmission line in place of the condensers in the circular array and the possible use of electronic or ionic valves with negative current-voltage characteristics, instead of the simple spark gaps, with the aim of generating continuous or modulated waves. Though oscillating circuits in which the energy is fed into the tuned circuit in parallel are highly developed, there seems to be no reason why series-fed circuits should not find equally useful applications in certain cases.

The principle of transmission described here has been the subject of a patent application by the University of New England (1958). It is hoped that the transmitter described will find use as a research tool.

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