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RESEARCH IN RING TRANSMITTER TECHNIQUES

By: L. T. DOLPHIN, JR. A. F. WICKERSHAM, JR.

Prepared for:

OFFICE OF NAVAL RESEARCH
WASHINGTON, D.C.
AND
ADVANCED RESEARCH PROJECTS AGENCY
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ARPA ORDER NO. 463

STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA

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June [redacted]65

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By: L. T. DOLPHIN, JR. A. F. WICKERSHAM, JR.

SRI-[redacted] *4548*

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ABSTRACT

The ring transmitter is a device for the generation of very high peak power radio-frequency pulses. Transmitter and antenna are combined in a single unit, which can excite a dish or be an element of an array. The ring consists of capacitors charged in parallel, each capacitor separated from its neighbors by spark gaps. The capacitors are discharged in series, though fast switches, to form a highly-selective resonant circuit, which is loaded primarily by its own radiation resistance.

The fast switches are usually pressurized, triggered spark gaps which allow an RF pulse to be turned on with a pulse-to-pulse jitter less than 5 nsec. Recent measurements indicate that jitter times below 1 nsec may be attainable.

A working model 20-Mc ring transmitter giving 3-Mw peak power pulses of 1 microsecond duration and two 6-Mc transmitters (1-2 Mw) have been built to date. The 6-Mc rings have been successfully triggered sequentially to produce a single coherent pulse of double length. Thus, it appears that CW power can be generated by using a number of rings fired sequentially. Studies have shown that passive circuit elements, coupled to the main ring, can be used to modify the pulse shape and length. In this manner, pulses of lengths 4-50 μsec have been obtained from the 6-Mc rings.

The ring transmitter is a promising and inexpensive device with application from VLF through UHF.

CONTENTS

ILLUSTRATIONS

I INTRODUCTION

The ring transmitter is a novel device for generating high power radio frequency pulses by the simple process of discharging capacitors through a tuned-loop resonant circuit. The loop also acts as a magnetic dipole antenna. This scheme for inexpensively generating high powers was suggested by Australian scientists working under Dr. Kurt Landecker.[1] The ring transmitter has been studied extensively at SRI for two years. The initial research on this project was reported earlier.[2-4] The present report summarizes recent findings and concludes that the Landecker transmitter is indeed a practical device.

Figure 1 is a sketch of the capacitors in a ring transmitter. Inductance derives from the posts, L, which interconnect the high-speed switches, S, with the N capacitors, C. The entire configuration, when the switches have been closed, forms a resonant circuit of total capacitance C/N and total inductance NL. Power loss occurs in the switches and in the radiation resistance. The radiation resistance is determined by the diameter of the ring. Graphs and formulas for calculating inductance, radiation resistance, power output, and pulse length were given earlier and will not be repeated here.[4]

Except for ohmic losses, which occur primarily in the switches, the energy stored in the capacitors, $W = 1/2NCV^2$, is radiated as a radio-frequency pulse. About 90 percent of the pulse power is radiated in a period $T = 2.3\ Q/\omega$ sec., where Q, the quality, is the ratio of ring reactance to resistance and ω is the angular frequency. Pulse lengths of the order of microseconds are readily obtained at the lower frequencies, and power levels above a megawatt have been realized.

Measurements on the first ring transmitters constructed at SRI, which used open-air spark gaps as switches, indicated power output to be three orders of magnitude below the expected levels. Study of the spark-channel formation process showed that spark-channel formation

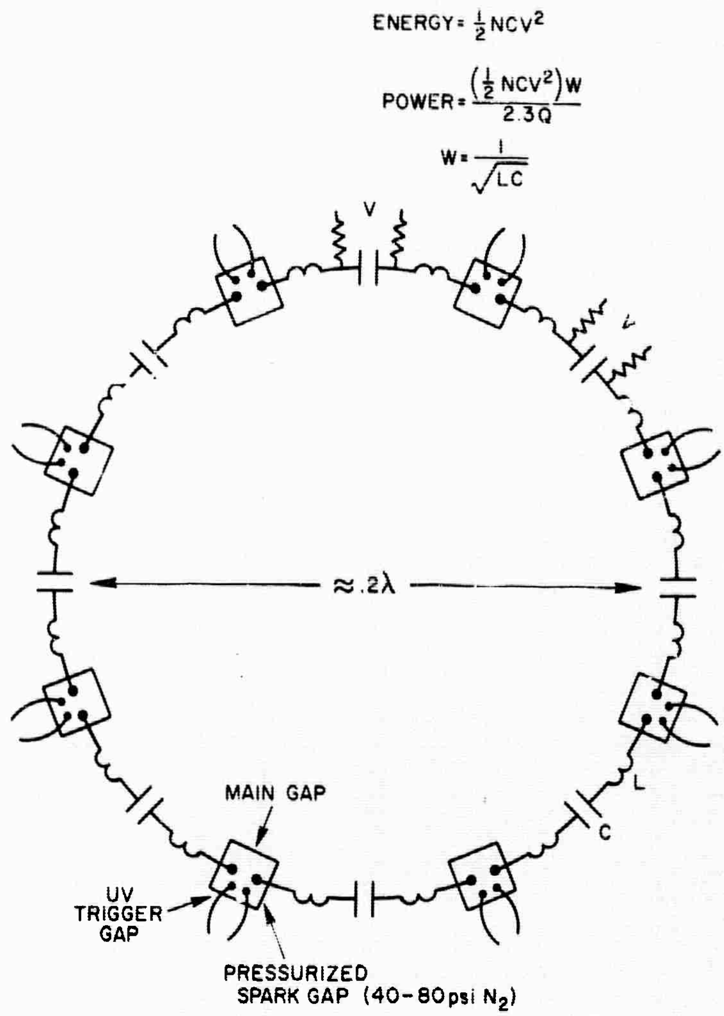


FIG. 1 BASIC RING TRANSMITTER

times varied nearly 100 nsec from gap to gap. These time intervals were long enough to cause a randomness in the initial charge redistribution around the ring. The randomness resulted in oscillations in unwanted modes and a waste of power.

The low-power-output problem was solved by pressurizing the spark gaps with several atmospheres of dry nitrogen. The high pressure permits closer gap spacing and greatly shortens the channel formation time. The pressurized spark channel has lower inductance and lower resistance, factors which improve transmitter characteristics and efficiency.

Recent studies have explored spark gap trigering methods for initiating each RF pulse from the ring transmitter at a precisely controlled time. Such control is desirable if the transmitter is to find application in phase-coherent radar applications. Figure 2 shows a pressurized gap with ultra-violet auxiliary electrodes. A high-voltage pulse from a fast trigger circuit is applied to the auxiliary electrodes to supply a flash of ultraviolet light. The ultraviolet flash, in turn, causes an immediate breakdown of the main gap.[5]

Parasitic elements, in the form of electric dipole elements, also have been added to the basic ring transmitter, and it has been shown that the ring can be used as the driving element in a Yagi array. It also has been shown that, as Landecker originally proposed, secondary parasitic tuned circuits can be added to driver rings in order to stretch the pulse duration or modify the pulse shape.

Since pulse length and maximum available peak power increase with decreasing frequency, the ring transmitter should be very useful at VLF. While the use of the ring transmitter in VLF applications is somewhat beyond the scope of the present research, Technical Memorandum No. 1[6] has been prepared for the benefit of research groups interested in high-power VLF systems; Ref. 6 recommended exploration of VLF applications of the ring transmitter.

Research under the present contract is continuing with particular emphasis on the development of a three-frequency, short-pulse, HF radar system and a phase-controlled 150 Mc ring transmitter.

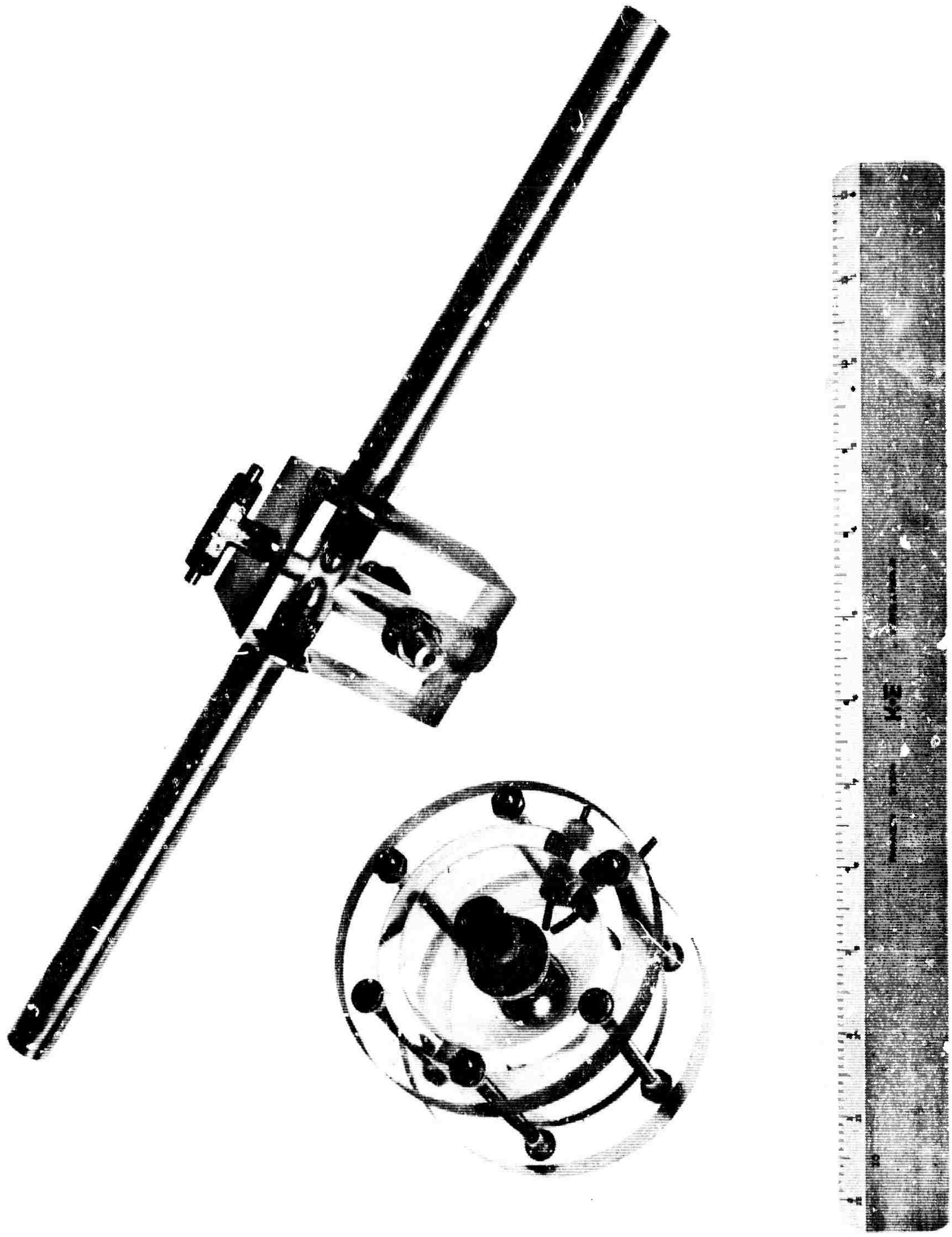


FIG. 2 PHOTOGRAPH OF PRESSURIZED SPARK GAP

II TWENTY-MEGACYCLE RING TRANSMITTER EXPERIMENTS

The 20-Mc ring transmitter has been used for many experiments in recent months. A photograph of this transmitter is shown in Fig. 3. Its design parameters are,

N = 67 capacitors, 365 picofarads each,

Charging voltage, V = 10-150 Kv,

Peak power at 50 Kv, 17 Mw,

Pulse length, 1 μsec.,

Q factor, 65

Radiation resistance, R^*, 23 ohms.

Radar echoes from this transmitter have been obtained on several occasions by using aircraft and local terrain as targets.[4]

In the photograph of the 20-Mc transmitter shown in Fig. 3, there are 67 connecting trigger leads, which were added for triggering the spark gaps, and in Fig. 4, there is a simplified sketch of the ultraviolet triggering scheme, taken from Godlove.[5] Experiments show that a rough degree of pulse-to-pulse synchronism can be obtained by triggering several of the gaps in the ring, since the ring has a natural tendency to avalanche breakdown (when one gap breaks down, the remaining gaps are overvoltaged and tend to break down promptly). (If precision is required, every gap in the ring should be triggered.) Originally, a central pressurized spark chamber was built, from which the 67 trigger cables extended radially to the 67 UV gaps. This arrangement provided triggering of the ring from an external trigger pulse, but not without a high degree of jitter, since the central chamber contained a multiplicity of spark gaps activated by a single spark in the center (Fig. 5). The central chamber was later replaced by a commercially available triggered spark gap, called a "trigatron" in trade literature. While jitter time below 20 or 30 nsec was not expected, according to the manufacturer of the gap, there was considerable advantage in having a single high-current discharge for the energizing of all 67 trigger leads.

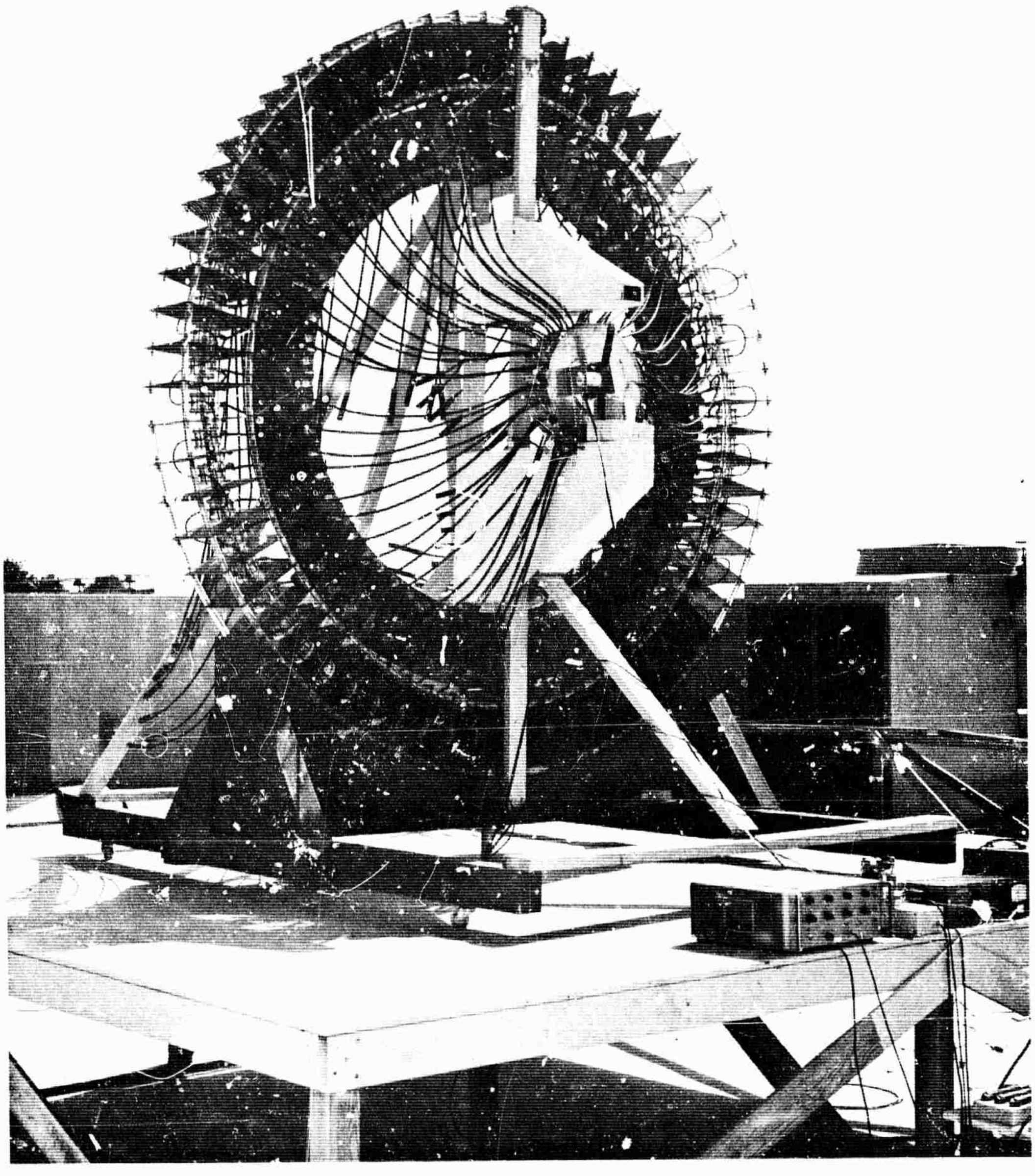


FIG. 3 PHOTOGRAPH OF 20-Mc TRANSMITTER

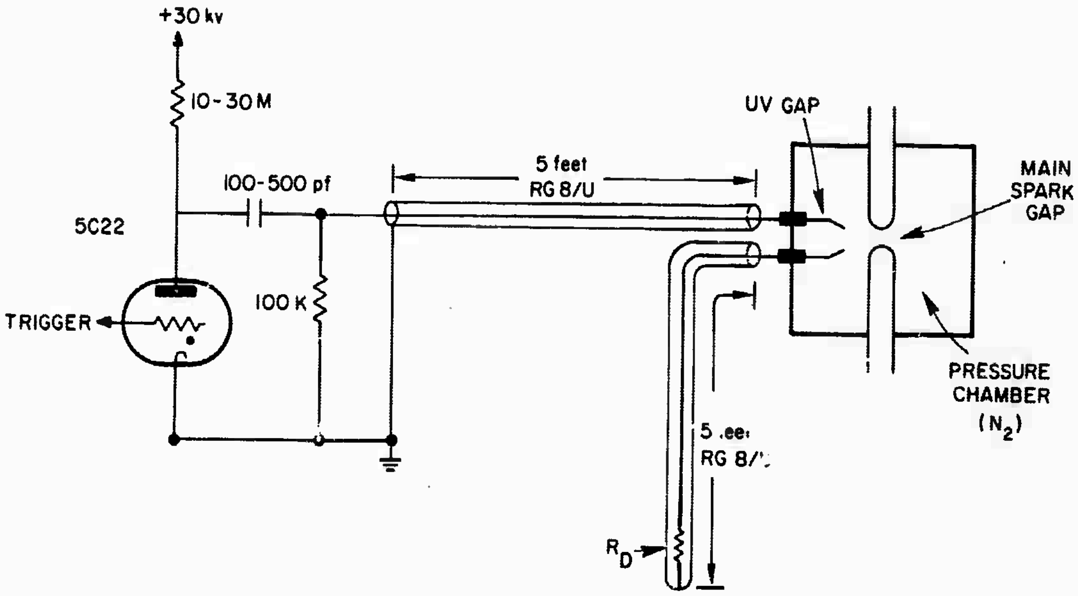


FIG. 4 BASIC FAST-PULSE ULTRAVIOLET TRIGGER CIRCUIT

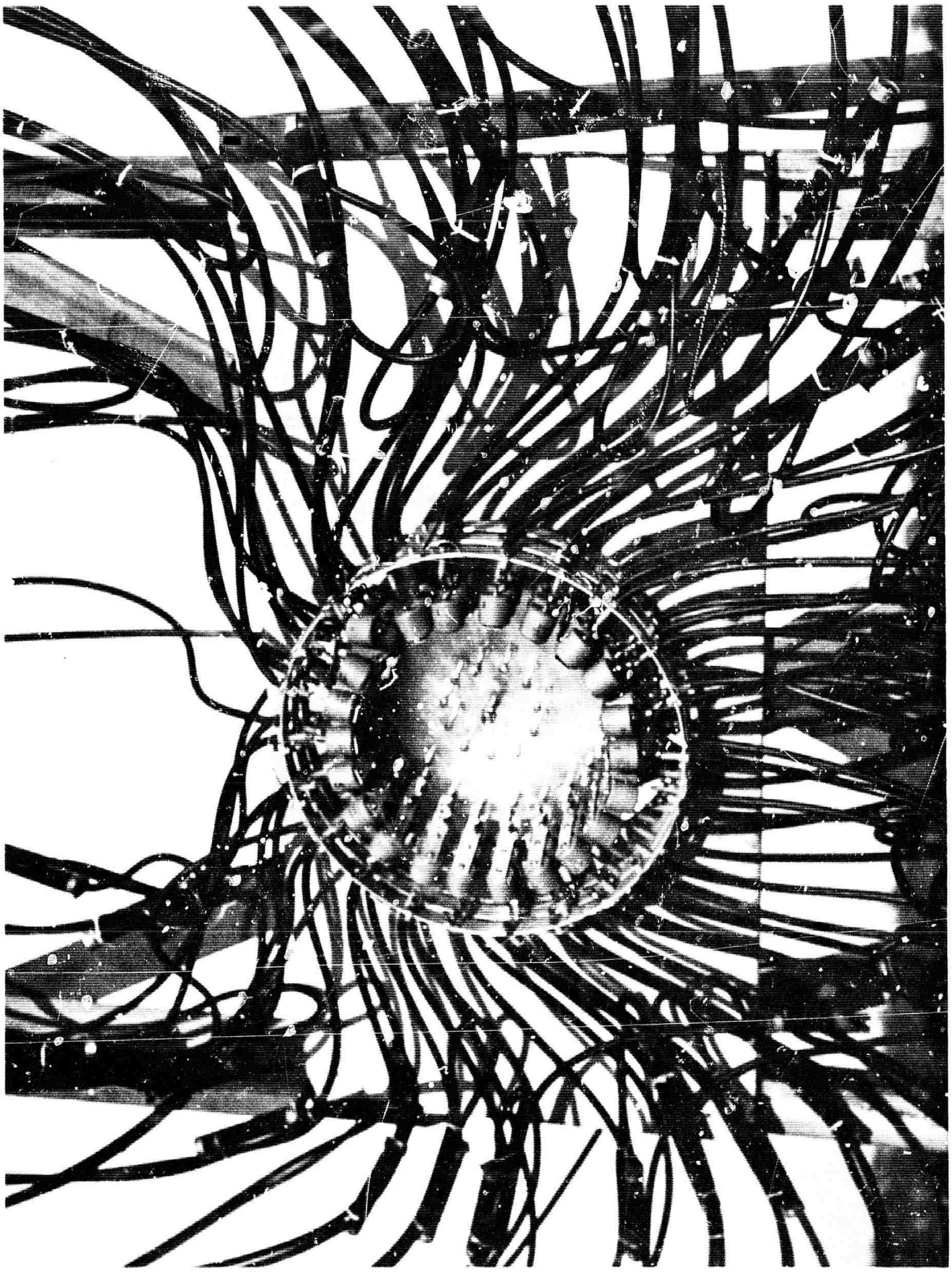


FIG. 5 PHOTOGRAPH OF CENTRAL SPARK-GAP CHAMBER

The trigatron was initiated by a 5C22 thyratron, and the thyratron, in turn, was driven by pulse amplifiers and a commercial high-speed pulse generator having an output pulse of 200 v with a rise time of 15 nsec.

Figure 6 is a photograph of superimposed traces of the triggering pulse on the screen of an oscilloscope. The PRF was about 1 pps. From the photograph it can be seen that the pulse-to-pulse jitter is about 3-5 nsec. In order to be sure that only overall jitter time was measured, the oscilloscope sampling probe was connected to a load resistor (R_d in Fig. 4) so that no signal could arrive at the oscilloscope until after the UV gap had discharged.

With the experimental arrangements described above, it was found that the RF pulse could be triggered with an accuracy of 3-5 nsec, provided the main gap voltage was adjusted within a few percent of the self-firing voltage. Study of the jitter time at various stages along the triggering chain indicated that the main source of jitter was the trigatron. When the thyratron was heavily and rapidly over-voltaged, it could be made to fire a single UV gap with a jitter of only 1-3 nsec. There is thus a possibility of reducing the jitter time to 1 nsec or less by replacing the trigatron by a single thyratron or a vacuum switch tube.

Triggering stability of the 20 Mc ring has proven to be somewhat marginal, requiring careful adjustment of operating voltages and operation at relatively low gap pressures (40 psi). This lack of good lock-in over a wider range of operating conditions probably derives from insufficient UV intensity in the main gaps. Future plans include modifying the gaps to provide improved trigger geometry and electrode materials. Such improvements may increase the UV intensity and its effectiveness.

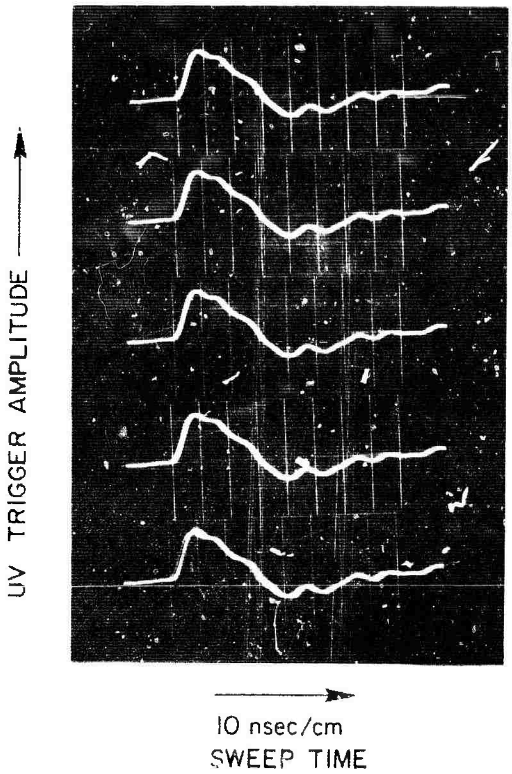


FIG. 6 ULTRAVIOLET TRIGGER PULSE USING IMPROVED CIRCUIT

III SIX-MEGACYCLE RING TRANSMITTER EXPERIMENTS

The ultraviolet triggering system described in the previous section originally was developed and tested on a small 6-Mc transmitter consisting of 20 capacitors of 1500 pf capacitance, arranged in a ring 0.15 wavelength in diameter (Fig. 7). This ring was less than the usual ring size of 0.2 to 0.3 wavelength; consequently, it had a radiation resistance of only 8 ohms. A second identical ring was built; also, a third was constructed with shorted gaps (Fig. 9). In addition, a large secondary ring was built to couple power from the driver rings and radiate it upwards (Figs. 8 and 9). Operating at a charging voltage of 30 kv, the two driver rings developed 1-2 Mw each and have pulse lengths of 4 μsec.

The pulse from one of the 6-Mc driver rings, observed by connecting a small antenna directly to the plates of a high-speed oscilloscope located a few dozen yards away from the ring, is shown in Fig. 10(a). An interesting characteristic of ring transmitters is shown in the figure: Rather than generating a pulse that is maximum during the first-half RF cycle and which decreases exponentially thereafter, all rings built to date generate pulses that take 4 to 8 RF cycles to reach a maximum. This characteristic rise time is believed to be the time required for the spark channel to become fully conducting. An appreciable fraction of the total power is spent heating and building the spark channel, which, after it is fully formed, has an RF resistance of about 0.1 to 0.3 ohm. Observation of transmitters operating from 5 to 50 Mc has shown that the buildup time is nearly a constant number of RF cycles, rather than a constant interval of time. The required channel formation time may not be a serious detriment to operation at higher frequencies. To some extent the formation time contributes to the narrow spectrum of the radiated pulse.

The effect of adding a tuned secondary circuit (a ring transmitter with shorted gaps) to the driver ring is shown in Fig. 10(b). The

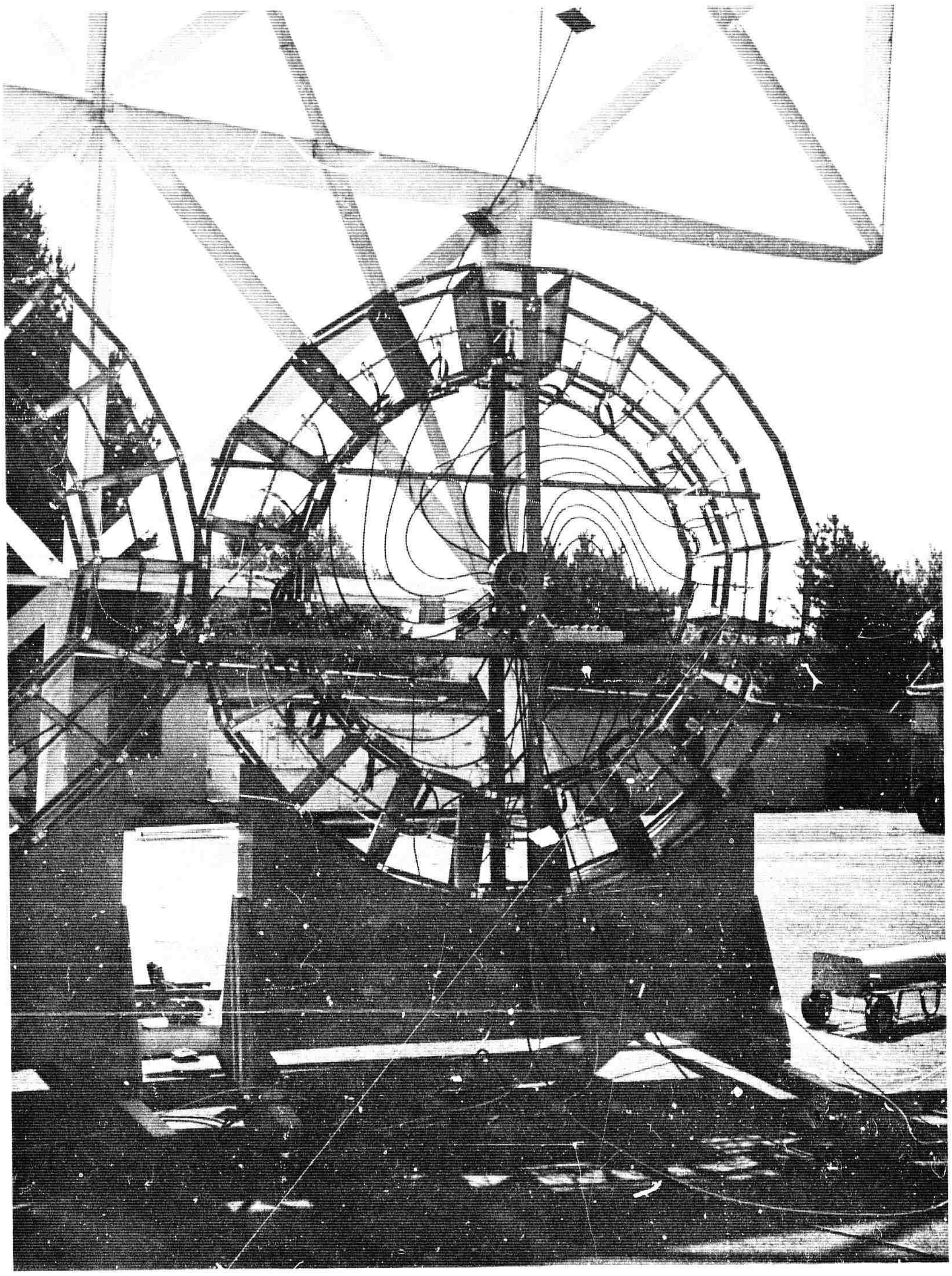


FIG. 7 PHOTOGRAPH OF 6-Mc DRIVER RING

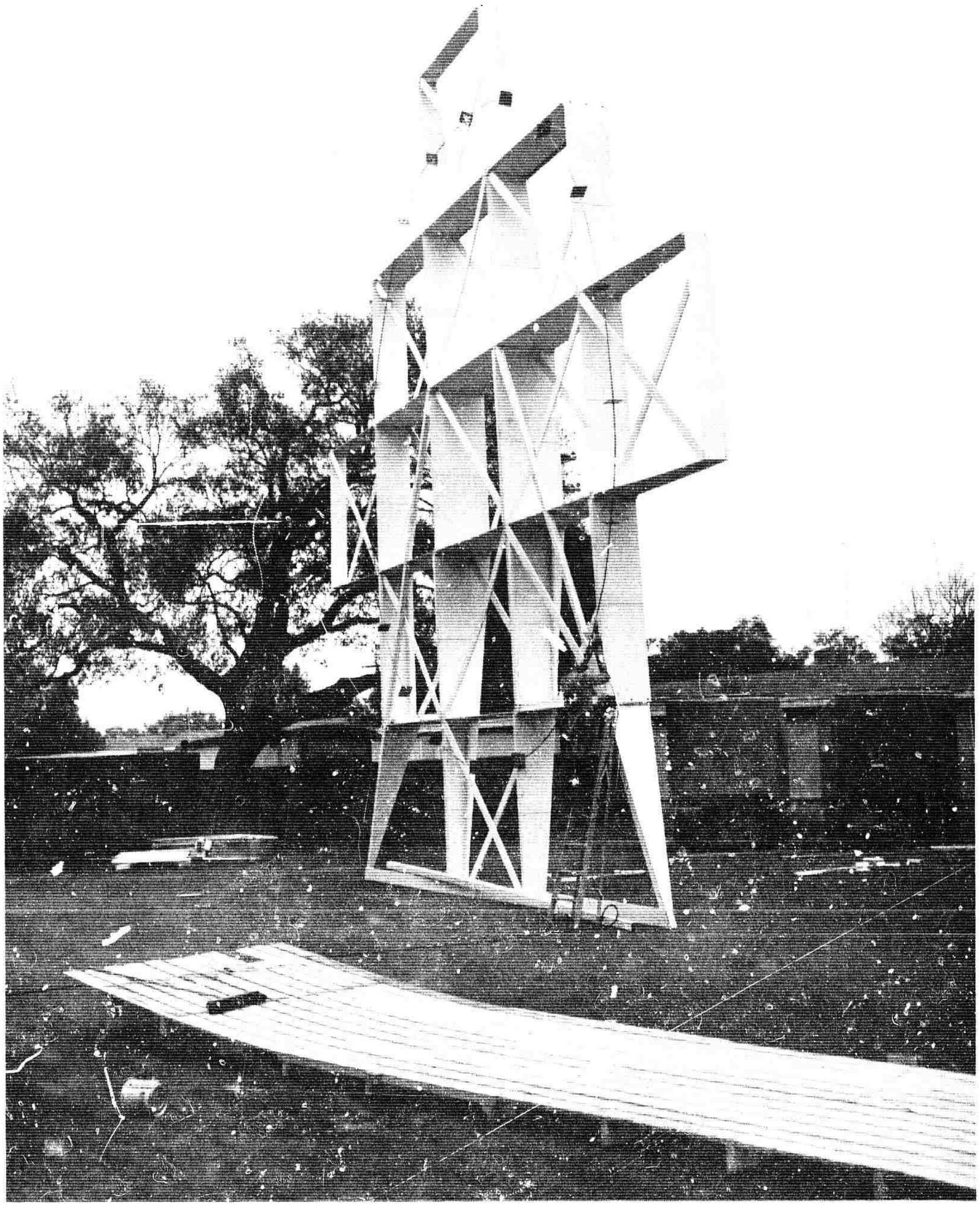


FIG. 8 PHOTOGRAPH OF 6-Mc RADIATOR RING

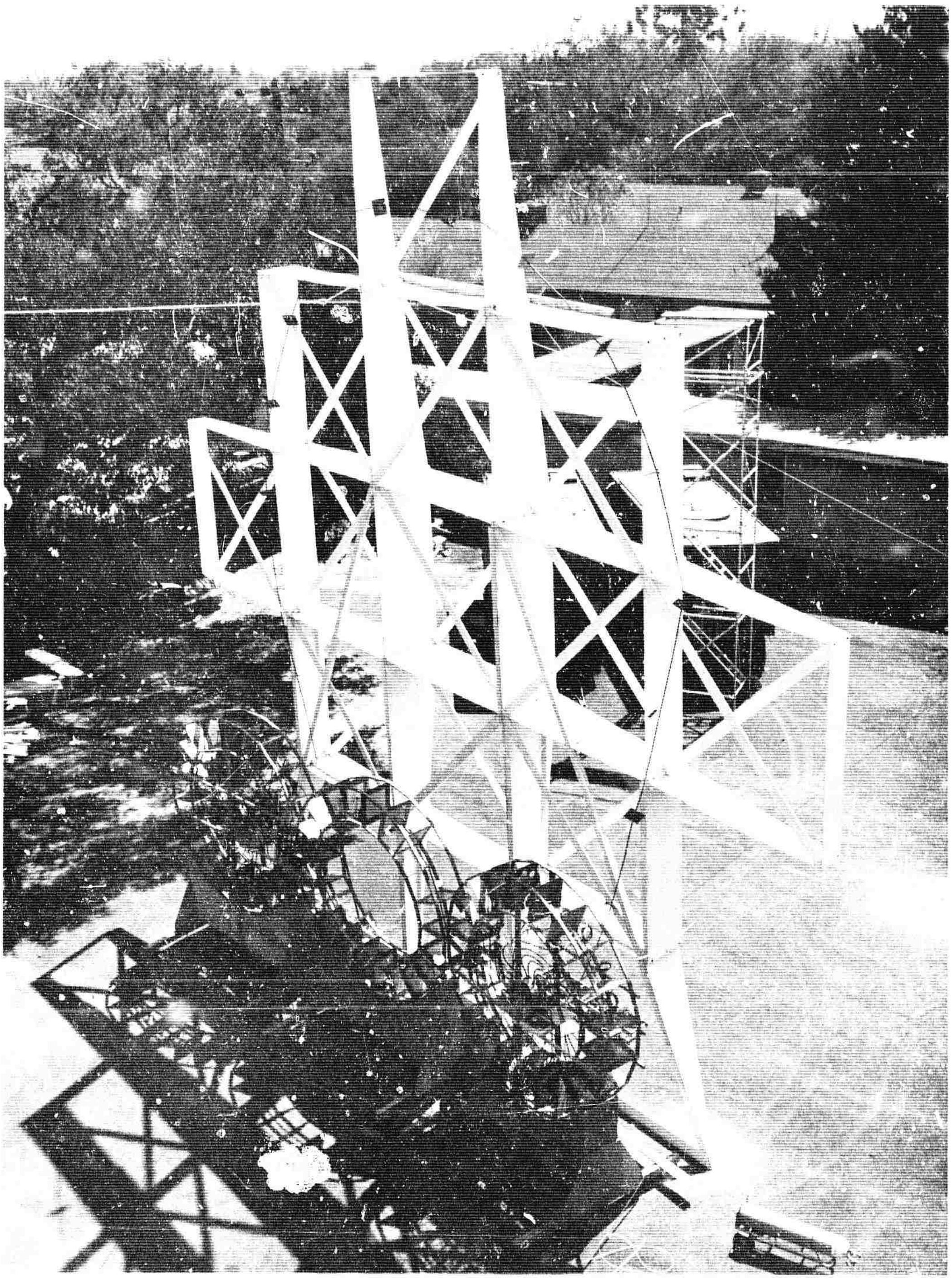
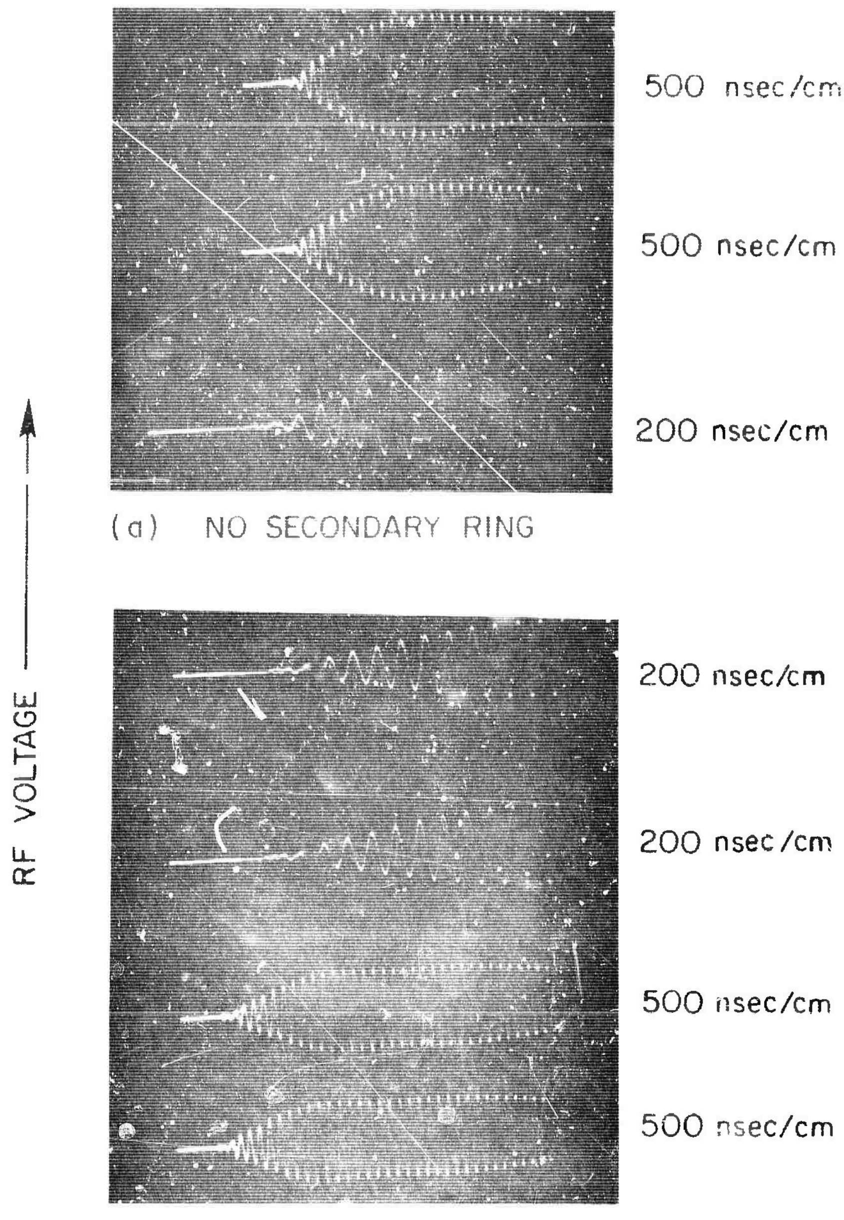


FIG. 9 PHOTOGRAPH OF COMPLETE 6-Mc SYSTEM



(a) NO SECONDARY RING

(b) WITH SECONDARY RING

FIG. 10 RF PULSES FROM 6-Mc RING TRANSMITTER secondary was magnetically coupled to the primary circuit, and since it had a higher operating Q than the primary, the energy exchange with the primary lengthened the total pulse. The effect of a high-Q secondary circuit is shown more clearly in Fig. 11, the photograph being taken at longer oscilloscope sweep times. Cardful adjustment of coupling coefficient and secondary circuit tuning lengthens the radiated pulse by a factor of 5 to 10. Although the average power during the pulse is reduced proportionally, a longer pulse is sometimes desired in radar work.

Pulse-to-pulse jitter in the RF signal from one of the 6-Mc driver rings is shown in Fig. 12. By triggering the oscilloscope with a master pulse generator, sequential RF pulses, one second apart, were superimposed for this photograph. Jitter times of 3-5 nsec were obtained, and stable performance was achieved by adjusting gas pressure, gap settings, and applied voltages.

The RF pulses from the two 6-Mc driver rings, triggered by the circuit shown in Fig. 14 are shown in Fig. 13. The rings were fired sequentially for this photograph. The second ring was fired at a time slightly after the first ring, so that a double pulse was obtained as shown. With an additional secondary ring, the double pulse in Fig. 15 was obtained. Since the second ring start time could be continuously adjusted, it was found that the rings could be made to fire simultaneously, or delayed up to many microseconds. Delay adjustment was sensitive enough to permit the relative phase of the two pulses to be accurately controlled and held with a precision of 3-5 nsec. Figure 16 shows the junction of the two pulses as the starting time of the second ring was varied with respect to the first. The fact that double pulses can be generated suggests the possibility of a CW transmitter. It is believed that a single ring can be operated at a PRF as high as 1000 to 10,000 pps, so that from 2 to 20 rings would be required for full CW operation. The individual rings are relatively inexpensive, and they could be arranged in the form of an array to achieve directional gain.

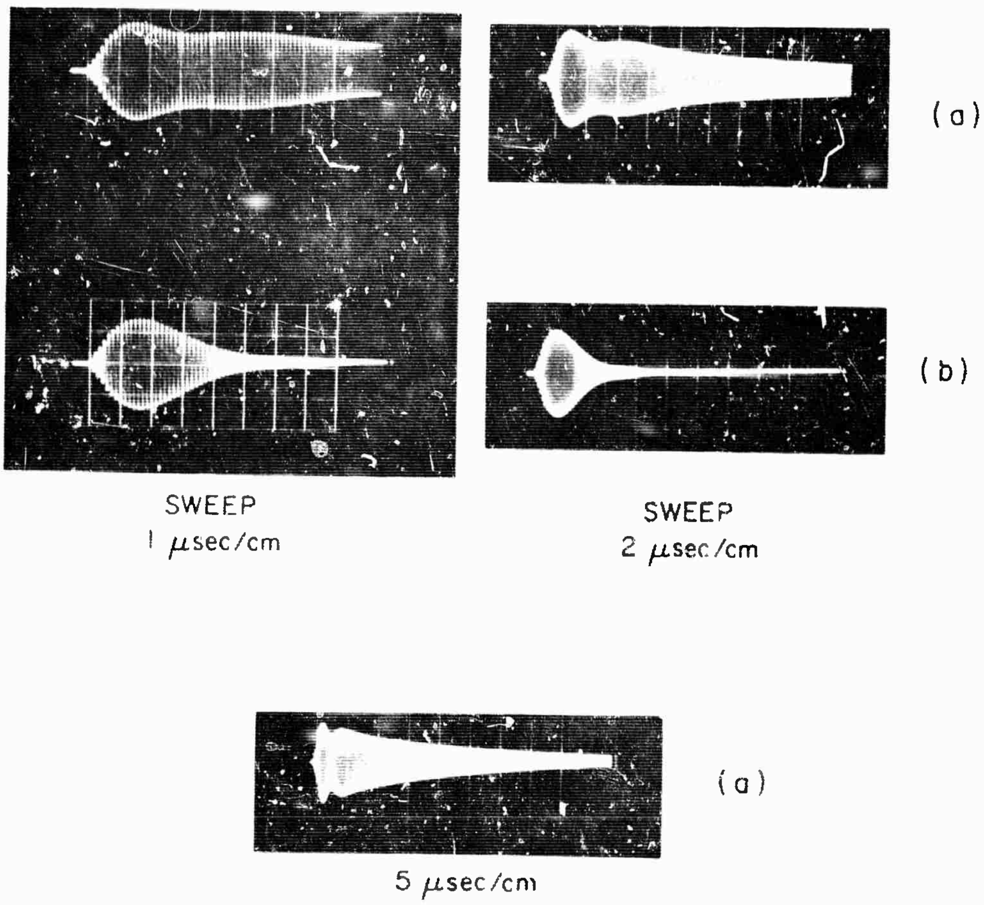


FIG. 11 RF PULSES FROM 6-Mc RING TRANSMITTER SHOWN AT INCREASED SWEEP TIMES

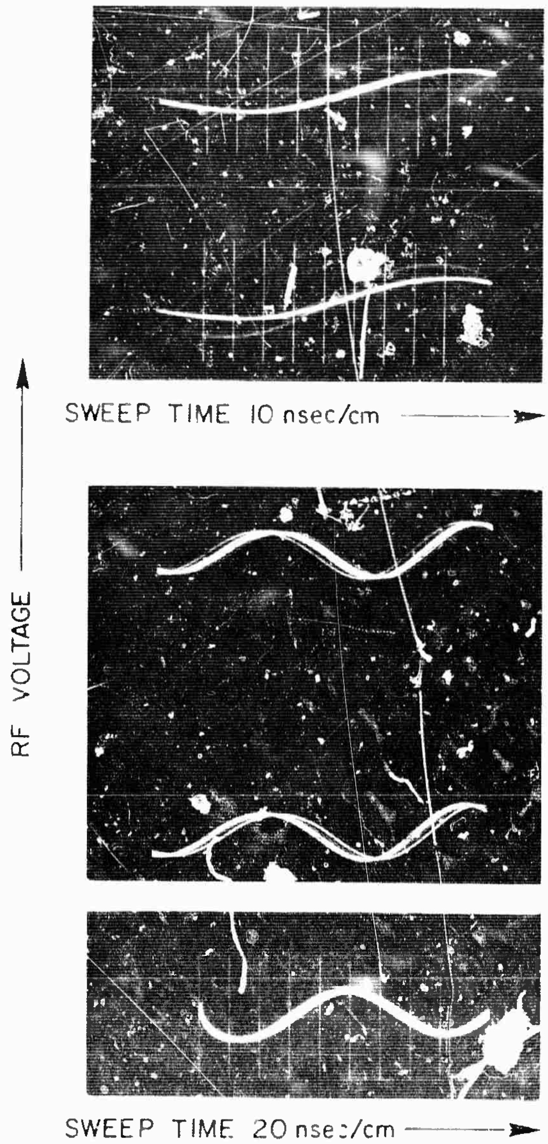


FIG. 12 6-Mc RF RADIATED SIGNAL SHOWING PULSE-TO-PULSE JITTER (PRF ≈ 1 pps)

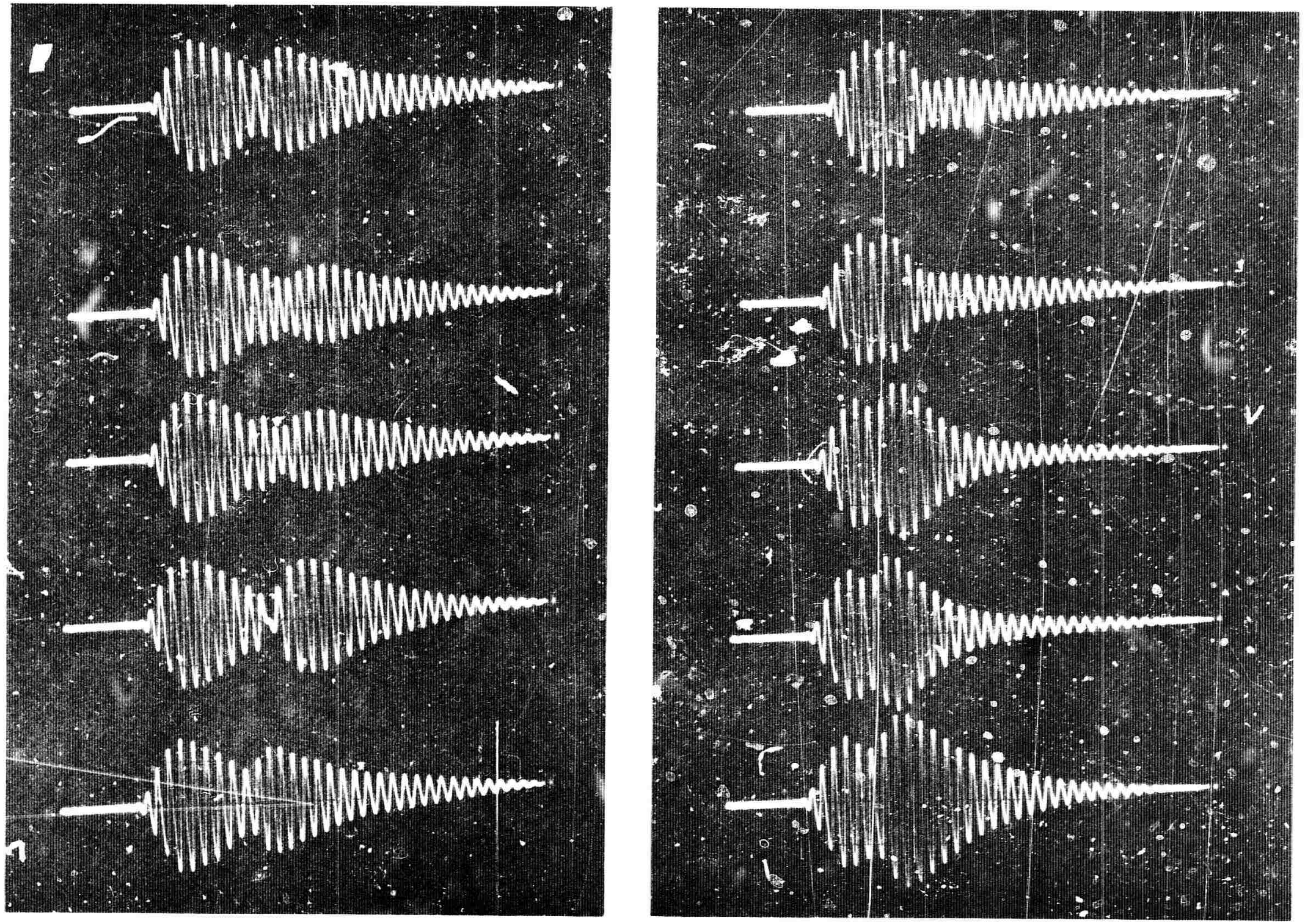


FIG. 13 COMBINED RF PULSE FROM TWO 6-Mc RINGS
(No secondary ring)

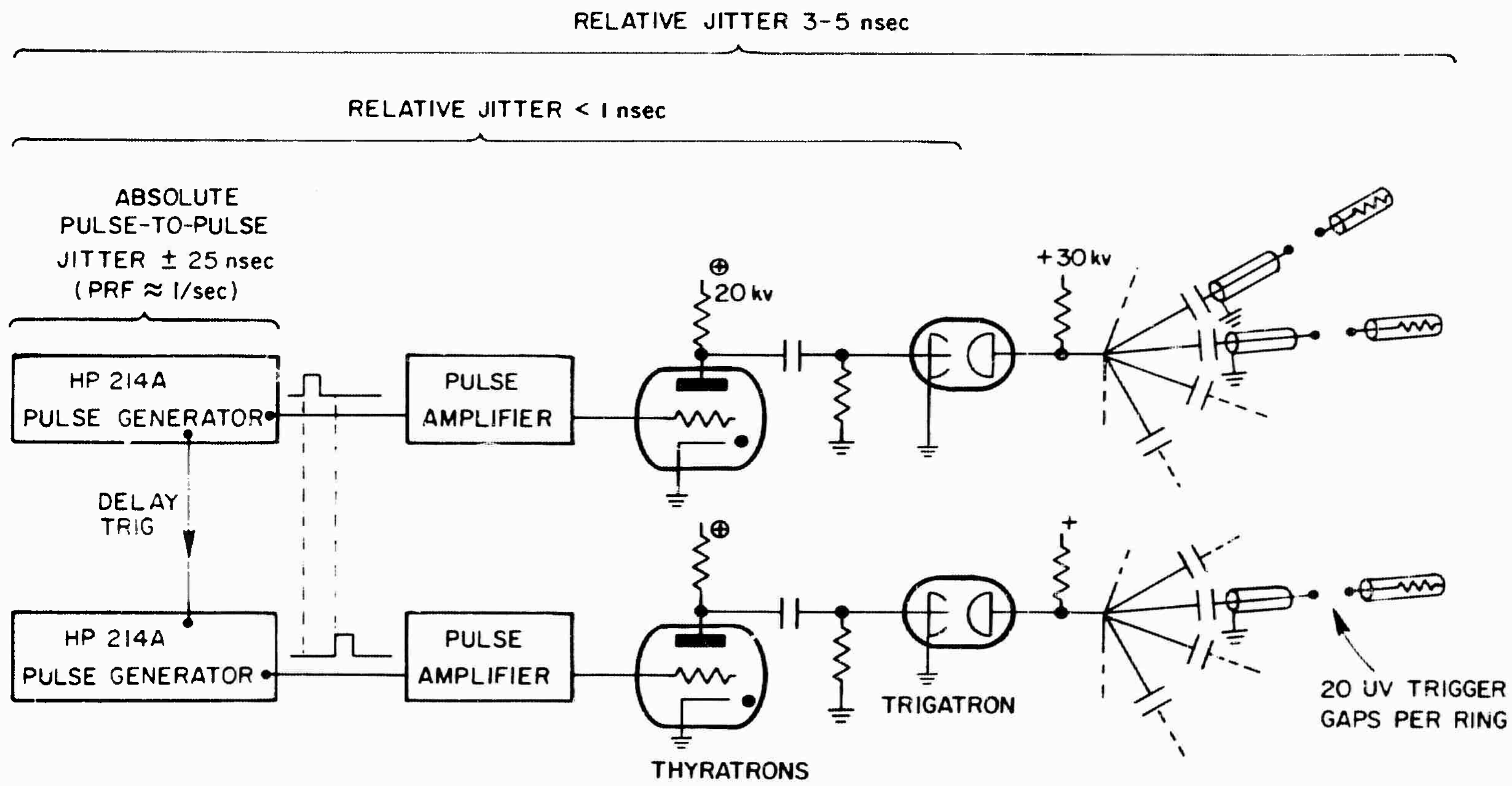


FIG. 14 SCHEMATIC OF DELAYED PULSE TRIGGER CIRCUIT

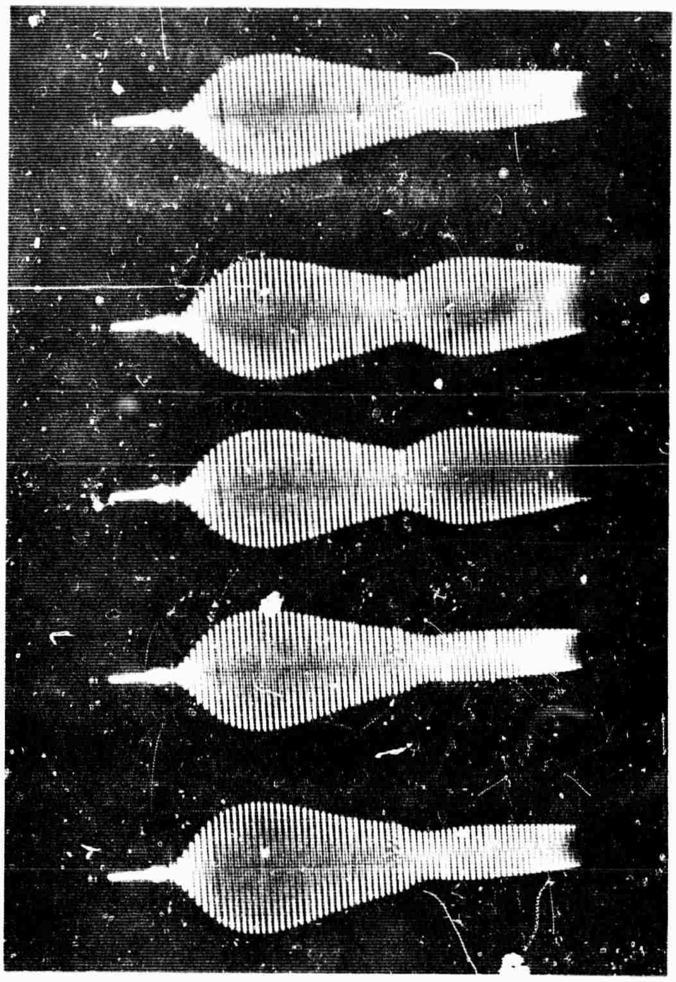


FIG. 15 COMBINED RF PULSE FROM TWO 6-Mc RINGS
(With secondary ring)

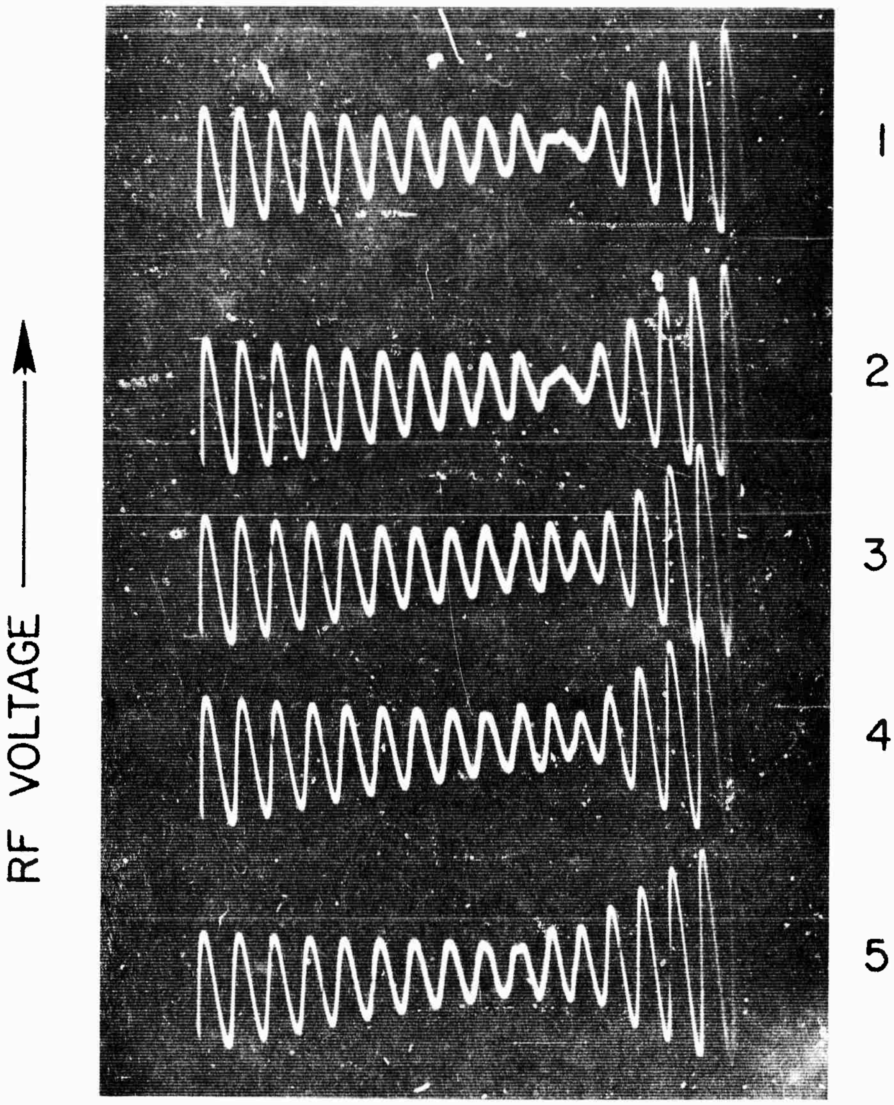


FIG. 16 PHASE JUNCTION OF TWO 6-Mc RINGS

Power output of a 6-Mc ring transmitter was estimated by measuring the current induced in a nearby ring having shorted gaps. It was concluded that the radiated power was 1-2 Mw and that the transmitter efficiency was about 50 to 70 percent. Radar echoes from the F-layer, received remotely, are shown in Fig. 17. Strength of the received echoes is consistent with the measured power of 1-2MMw. The signal from the transmitter was relatively narrow, having a bandwidth of about 200 kc. This is approximately what is expected for a pulse length of 4 μsec.

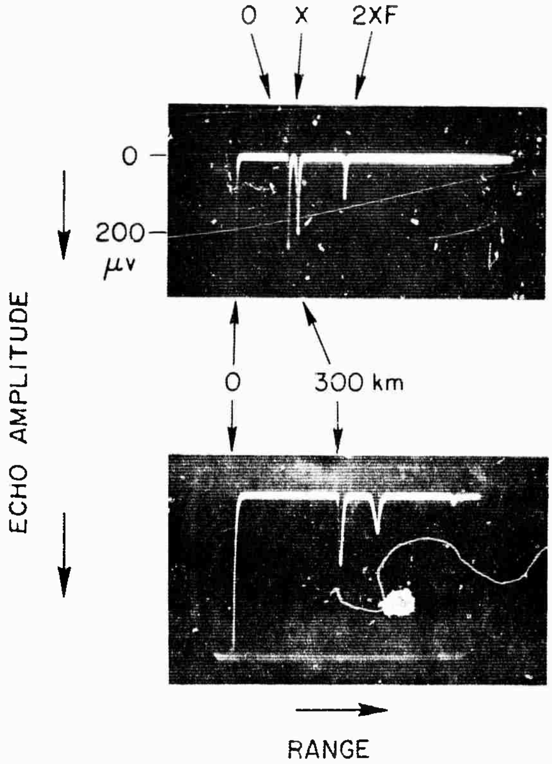


FIG. 17 F-LAYER ECHOES AT 6.55 Mc

IV ANTENNA CHARACTERISTICS OF RING TRANSMITTERS

At frequencies as low as 6 Mc, the radiation characteristics of a ring transmitter may be somewhat unsatisfactory since the ring diameter may be so small compared to a wavelength that radiation resistance becomes less than ohmic resistance. This could mean that more power would be lost in heat than would be radiated at radio frequencies. A possible way to increase the radiation resistance of a ring, and also achieve some control of the radiation pattern, is to couple the ring to parasitic dipole elements. For example, a ring transmitter could be cut in half and excited over a ground plane; in addition, horizontal or vertical dipole elements could be coupled to the half ring to obtain vertical or horizontal directive beams.

In the case of a half ring coupled to one or more horizontal dipoles--to achieve a vertical beam--the efficiency is difficult to estimate. The coupling efficiency of half ring to dipole would increase as the dipole is brought closer to the ring, but the radiation resistance of the dipole decreases rapidly as it is brought closer to the ground plane. In order to test the practicality of a half ring and dipole system, and to determine the optimum coupling condition, we measured the efficiency of a scaled-down system at 107.5 Mc.

The test procedure and results of attempting to increase the radiation resistance of a small half-loop excited through a conducting ground plane are shown in Figs. 18 and 19. The effective radiation resistance was increased first by coupling the loop to a half-wave dipole and second by coupling to a combination of a half-wave dipole and director element.

As the distance between loop and dipole is decreased, the coupling and radiated power increase; however, a point is reached where further decrease in distance results in less power radiated because the radiation resistance of a dipole over a ground plane decreases with distance

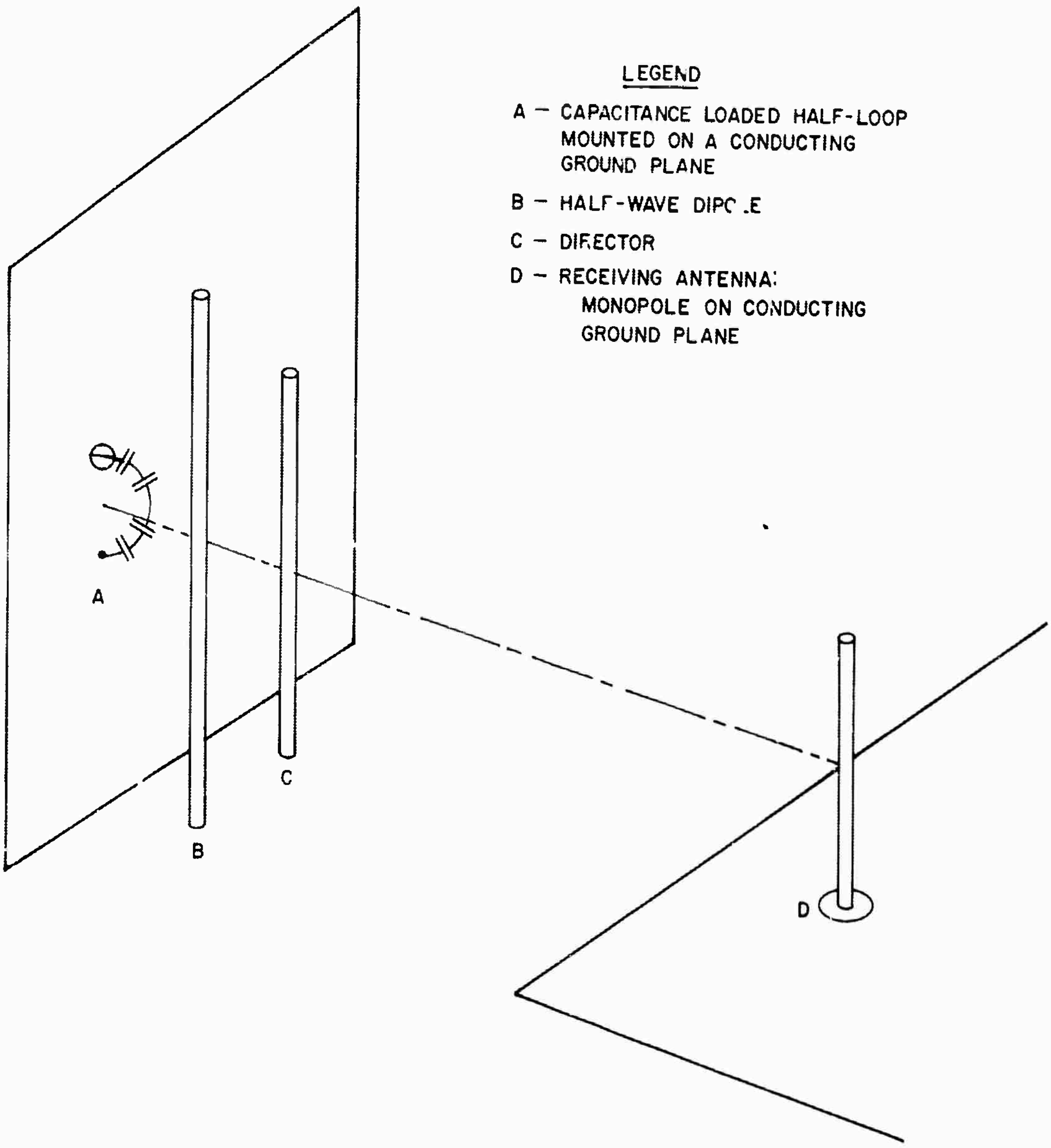


FIG. 18 EXPERIMENTAL ARRANGEMENT FOR MEASURING THE INCREASE IN EFFECTIVE RADIATION RESISTANCE RESULTING FROM COUPLING OF PARASITIC ELEMENTS TO AN EXCITED ANTENNA

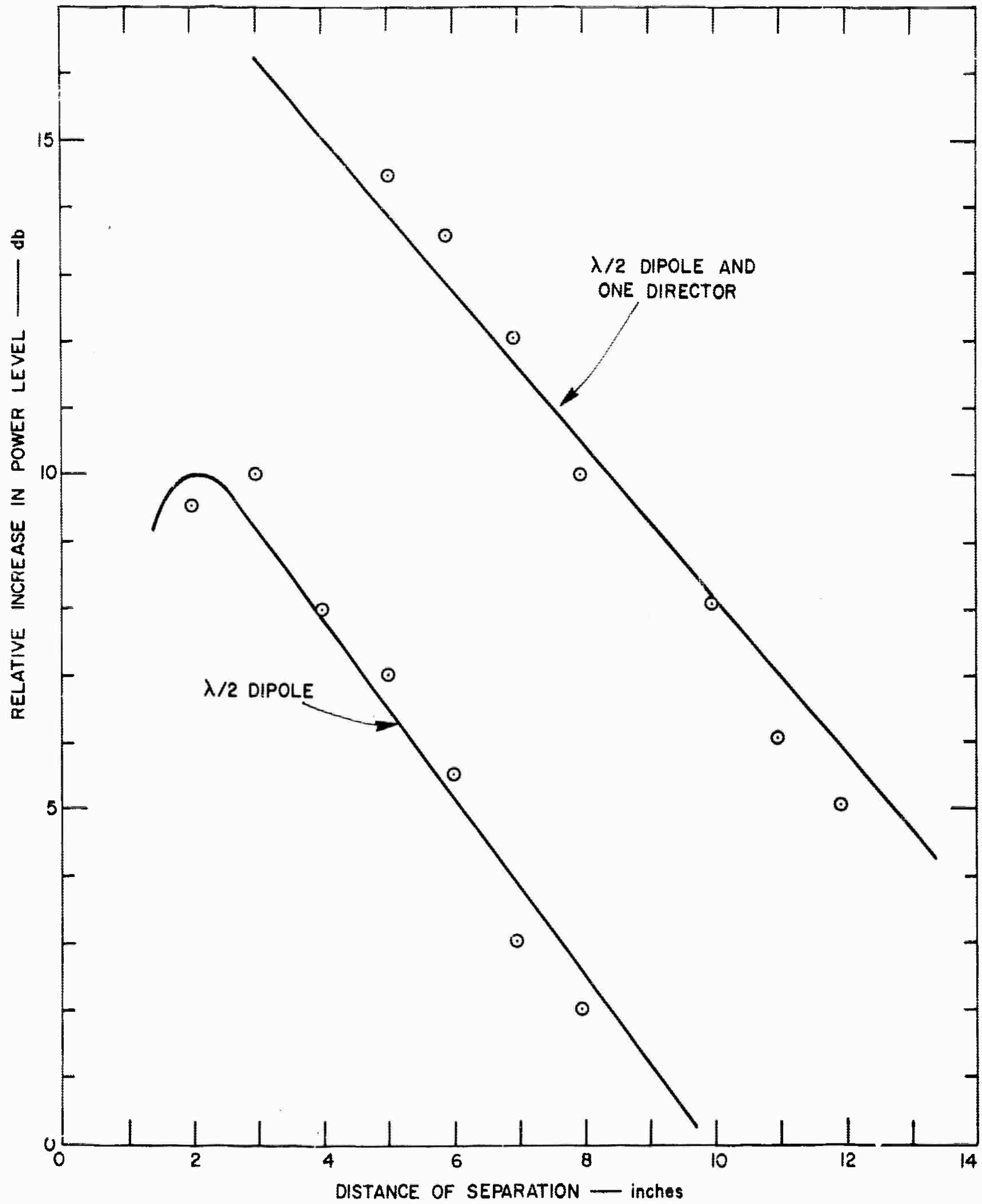


FIG. 19 INCREASE IN RADIATED POWER FOR VARIOUS DISTANCES OF SEPARATION BETWEEN DIPOLE AND HALF LOOP
(Distance between dipole and director held at 8 in.)

from the ground plane. From the measurements we see that an optimum point was reached when the dipole was 2 to 3 inches from the loop (6 to 7 inches from the ground plane).

The effective radiation resistance can be further increased by adding a director element. The 6-db increase in received power (Fig. 19) is much larger than can be accounted for by directivity alone.

The RF frequency was 107.5 Mc ($\lambda = 2.79$ m or 110 in.) and the diameter of the loop was 4 in. The loop was loaded with four 30-pf capacitors to simulate a spark-gap ring transmitter. It was excited by an RF oscillator through a series-variable capacitance of 700 pf. The series capacitor, mounted behind the ground plane, was used to tune and match the load to the oscillator during measurements. The receiving antenna was a monopole about 30 ft from the loop. A crystal detector was mounted directly under the monopole and the rectified power was measured with a Hewlett-Packard Model 415B Square Law Detector, tuned to the 300-cps modulation frequency.

The radiation resistance of a small loop is $R = 1.92 \cdot 10^4 (d/\lambda)^4$ ohms; for the loop tested, this formula gives $R = 0.535$ ohms. The radiation resistance of a dipole parallel to a ground plane and at a height of 6/110 wavelengths is approximately 10 ohms. Since radiated power is proportional to radiation resistance, we should expect the addition of the dipole to increase the power level by a factor of 10.0/0.535, or about 12.7 db. The measurements show an increase of only 10 db, so we conclude that the coupling efficiency must have been about 50 percent. The effective radiation resistance realized with half-loop, dipole, and director was about 11 ohms, which is satisfactory.

At higher frequencies radiation resistance is no problematical, but it becomes difficult to store sufficient energy in a single ring. This, in turn, leads to the problem of synchronizing several rings to achieve high power output. Consider, for example, the range at which a target of one square meter cross section ($\sigma = 1$) can be detected by a radar consisting of an array of 100 synchronized rings operating at a frequency of 150 Mc ($\lambda = 2$ m). We assume that the array directivity and the receiving antenna directivity are both 33 db ($G_r = G_t = 2 \cdot 10^3$). With a pulse width of 0.2 μsec, the bandwidth will be about 5 Mc; thus, the noise power will be $kTB = (1.38 \cdot 10^{-23}$ joules/deg.)(300°K) ($5 \cdot 10^6$ cps) $= 2.07 \cdot 10^{-14}$ watts. Allowing a 10:1 signal-to-noise ratio, we find the required receiver power will be $P_r \approx 2 \cdot 10^{-13}$ watts. We take the peak pulse power to be 1 Mw per ring; thus, the total transmitter power will be $P_t = 100$ Mw. Putting these numbers into the range equation, $P_r = P_t G_t G_r \lambda^2 \sigma / (4\pi r^2)^2$, and solving for the range, we find r = 2,670 km., or about 1700 statute miles.

A single 150 Mc ring can easily be built with about 20 capacitors of 40 pf capcitance each, and operated at 50 kv. Such a ring will store about 1 joule of energy and radiate 1 to 5 Mw peak power, assuming efficiencies between 20 and 100 percent, respectively. Charging voltages up to 150 kv are considered feasible as a means of raising the power output by an order of magnitude.

A 150 Mc pressurized ring, about 1.5 ft. in diameter and capable of storing 1 joule, is now under construction. If the power output is satisfactory and coherent energy is obtained, several such rings will be built.

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