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DEVELOPMENT OF AN RF NEAR-FIELD EXPOSURE SYNTHESIZER (10 to 40MHz)

U.S. DEPARTMENT OF HEALTH, EDUCATION AND WELFARE / Public Health Service
Center For Disease Control / National Institute For Occupational Safety And Health

DEVELOPMENT OF AN RF NEAR-FIELD EXPOSURE SYNTHESIZER
(10 to 40 MHz)

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Public Health Service
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PREFACE

Field measurements performed by the Physical Agents Effects Branch have revealed that the majority of industrial radiofrequency (RF) power sources operate at specific frequencies (13.56, 27.12 and 40.68 MHz) within the Federal Communication Commission (FCC) assigned Industrial-Scientific-Medical (ISM) frequency bands. Since field strength levels in the ISM bands are not regulated by the FCC, workers operating industrial RF sources can receive a greater radiation exposure than those operating communications transmitters and other RF sources at regulated frequencies. Moreover, because of the close proximity of workers to industrial RF power sources, high personnel exposure levels occur under near-field conditions (less than 1 meter to RF power sources). The need for investigating the possible hazards associated with these radiation exposures is clearly indicated.

The unique RF synthesizer described in this report is capable of simulating near-field exposure conditions commonly encountered in the work environment. This report covers the design, fabrication, and testing of the complete facility. The synthesizer design enables exposures to be generated for bioeffècts laboratory studies as well as for calibration of RF exposure monitors essential for conducting biological research. Requirements necessitated the capability to independently generate the electric and magnetic fields. The ratio of the electric to the magnetic field can be adjusted to reproduce actual occupational exposure conditions. Tuning data is available for nine calibration frequencies with an operating frequency range 10 to 40 MHz.

CONTENTS

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ABSTRACT

This report describes work done by the Electromagnetics Division of the National Bureau of Standards for the National Institute for Occupational Safety and Health (NIOSH) involving the design, construction, installation and testing of a prototype RF near-field synthesizer. The purpose of the contract was to provide a means of independently generating high-level electric and magnetic near fields in the frequency range 10 to 40 MHz. These fields are to be used in various ratios by NIOSH in their program for the evaluation of occupational hazards resulting from exposure of industrial personnel to strong, non-ionizing, RF radiation. The program will include determination of the biological effects of such exposures as well as the calibration and intercomparison of hazard-level electric and magnetic near-field probes necessary for such studies.

The synthesizer consists of a balanced, parallel-plate strip line to generate the "desired" electric (E) field, and a single-turn quadruple-feed inductor placed parallel to and midway between the plates to generate the "desired" magnetic (H) field. Methods used to reduce the "unwanted" E- and H-field components associated with the above, as well as the methods used to reduce the coupling between the two field systems are discussed. The result is a synthesizer in which the electric- and magnetic-field components can be adjusted essentially independently over wide ranges of magnitude, phase difference, and relative spatial orientation to simulate various near-field configurations. An RF driving power of up to one kilowatt is required for each field system.

Previous research has been largely limited to the use of plane-wave fields for evaluating RF biological hazards. Since industrial workers are exposed primarily to RF near fields, this new device will allow researchers to accurately investigate any near-field effects that may occur at high field levels.

Keywords: Near field; RF biological hazard, RF field hazard; RF field synthesizer; RF radiation-exposure.

1. INTRODUCTION

This report describes work done by the Electromagnetics Division of the National Bureau of Standards for the National Institute for Occupational Safety and Health (NIOSH) involving the design, construction, installation and testing of a prototype RF near-field synthesizer. The purpose of the contract was to provide a means of independently generating high-level electric and magnetic near-fields in the frequency range 10 to 40 MHz. The RF near-field synthesizer will be used by NIOSH to evaluate RF biological hazards to industrial personnel resulting from exposure to strong non-ionizing RF radiation. This evaluation effort will include exposure of biological specimens and experimental animals in the RF near-field synthesizer, as well as the calibration and intercomparison of RF electric and magnetic near-field probes essential to such studies.

Two different sizes of synthesizers are necessary in order to cover the above frequency range. The larger covers the range from approximately 10 to 30 MHz, and the smaller from approximately 20 to 40 MHz. Each synthesizer consists of: (a) a balanced, parallel-plate strip line to generate the "desired" electric (E) field; and (b) a single-turn quadruple-feed inductor placed parallel to and midway between the plates to generate the "desired" magnetic (H) field. It is generally known from Maxwell's equations that in addition to the "desired" E and H fields in (a) and (b) respectively, the electric field in (a) is accompanied by an "unwanted" magnetic field, and the magnetic field in (b) is accompanied by an "unwanted" electric field.

It turns out that the "unwanted" magnetic field produced by the parallel-plate strip line is negligibly small for the plate size, frequency, and the magnitude of E being used. The magnitude of the "unwanted" E-field produced by the single-turn inductor was reduced by an order of magnitude in the central portion of the inductor by the expediency of using a multiple-feed rather than the conventional single feed. This means that under the conditions of use the single-turn inductor can generate a fairly "pure," high-level H field, and the parallel-plate line a fairly "pure," high-level E-field over the above frequency range.

The electric and magnetic coupling between the two field systems of each synthesizer was minimized by operating each system in a balanced mode and with the required mutual symmetry. There is no observable cross-coupling even when the loop is rotated out of its initial plane of symmetry by any desired angle. As a result, the electric- and magnetic-field components can be adjusted essentially independently over wide ranges of magnitude, phase difference, and relative spatial orientation in order to simulate various near-field configurations. An RF driving power of up to one kilowatt is required for each field system.

Previous research in RF biological hazards has been largely limited to the use of plane-wave fields for making clinical studies. Since industrial workers are exposed primarily to RF near-fields, this new device will allow researchers to accurately investigate any near-field effects that may occur at high-field levels. If the above considerations are not taken into account the exposure levels are not known and dose effects studies previously performed are meaningless. The practical mks International System of Units (SI) is used throughout this report.

2. THE RF MAGNETIC-FIELD GENERATOR

2.1 The Physical Characteristics of the Loop Inductors. The RF magnetic-field generator of each of the two synthesizers consists basically of a balanced single-turn inductor. The larger of the two inductors has an average diameter, d_1, of approximately 50 cm, and the smaller 30 cm. Both are formed from copper tubing having an outside diameter, d_2, of 4 cm and a wall thickness of 1.0 mm. The two inductors have low-frequency inductances, L, of approximately 0.8 and 0.4 microhenries, respectively, as determined from the following expression [1]:

$$L = 2\pi\, d_1 \left[2.303 \log_{10}\left[\frac{8d_1}{d_2}\right] - 2\right] \cdot 10^{-3}, \qquad (1)$$

where d_1 and d_2 are in centimeters, and provided $d_1/d_2 > 5$. The diameter selected was the result of a compromise to make the inductors as small as possible (to maintain a reasonably high self-resonant frequency) while still providing sufficient space to accommodate the test sample during exposure without undue crowding. Large-sized copper tubing was used to minimize the RF conductor losses and consequently the RF driving power requirements of the source, as well as for reasons of mechanical strength.

The choice of a single-turn rather than a multiple-turn inductor was made because of the following desirable characteristics:

(a) a lower distributed capacitance;

(b) a higher resultant self-resonant frequency;

(c) a lower "unwanted" electric-field strength due to a lower reactive voltage drop; and

(d) less shielding of the "desired" electric field of the associated parallel plates previously mentioned. This shielding would in effect produce a distortion of the spatial distribution of the "desired" electric field which would increase with the number of turns of the inductor.

All joints in the loop are high-temperature silver-brazed to provide maximum electrical conductivity, mechanical strength, and water tightness (for cooling to be discussed later).

2.2 The Electrical Characteristics of the Loop Inductors. Each inductor [2,3] is driven, in effect, by four synchronous RF generators located symmetrically 90 degrees apart around the loop periphery. While these generators are in-phase with respect to each other, diametrically-opposite generators create electric fields which are spatially 180 degrees out of phase and therefore cancel at the center of the inductor. This provides for an order-of-magnitude (10:1) reduction in the "unwanted" electric field that would otherwise exist in the central portion of the loop if driven by only one generator [4]. The magnetic field remains unaffected since only those components of the electric field that do not contribute to Curl $\bar{E}$ are being cancelled.

Instead of a single gap as found in the usual "shielded" loop [5,6], these loops have four gaps (90 degrees apart) as shown in Figure 1. The four driving voltages are obtained from the two matching networks shown, and are fed-in coaxially and appear across the respective gaps, in-phase with respect to each other. The inner conductor of the coaxial drive is 2.0 cm diameter copper tubing with a 1.0 mm wall thickness. With the electrical balance or symmetry that must be maintained around the periphery of the four-gap loop, four voltage nulls or zero-potential points result, one midway between each of the four gaps. These null points lie on two orthogonal image planes intersecting at the center of the loop. This permits the loop to be both mounted mechanically and driven electrically from two diametrically opposite null points as indicated in Figure 1. Since each of the matching networks shown has a balanced (push-pull) output, each, in effect, provides two of the four driving voltages, mentioned above, in the proper phase relationship. An exploded view of the larger four-gap loop inductor and the coaxial inner conductors is shown in Figure 2. A view of the assembled loop inductor and its associated matching networks is shown in Figure 3.

The "unwanted" electric-field strength, E, in the plane of the loop is proportional to both the operating frequency, $\omega/2\pi$, and the distance from the center, r, as shown by the following expression [4]:

$$E = -j \frac{\omega\mu H r}{2}, \quad V/m. \tag{2}$$

For a value of magnetic field strength, H, at the center of the loop of 50 A/m (the maximum specified by the sponsor) the electric field at a distance, r, equal to one quarter of the loop radius, varies from approximately 100 V/m at 10 MHz to 400 V/m at 40 MHz.

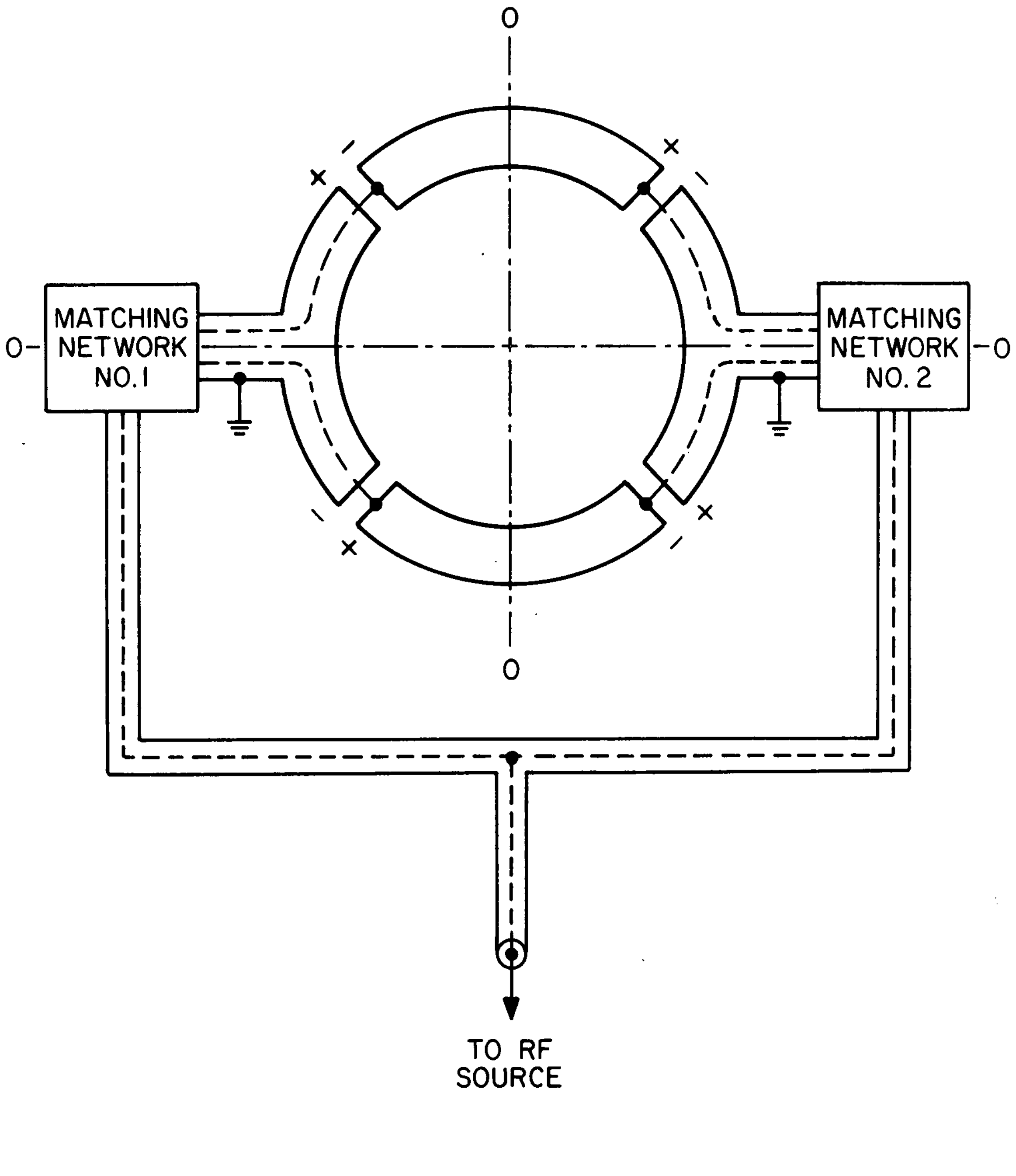

Figure 1. A Block Diagram of the RF Magnetic-Field Generator Showing the Four-Gap Shielded-Loop Inductor and the Associated Tunable Matching Networks for Use from 10 to 40 MHz. The Two Orthogonal Image Planes are Shown Intersecting at the Center of the Loop.

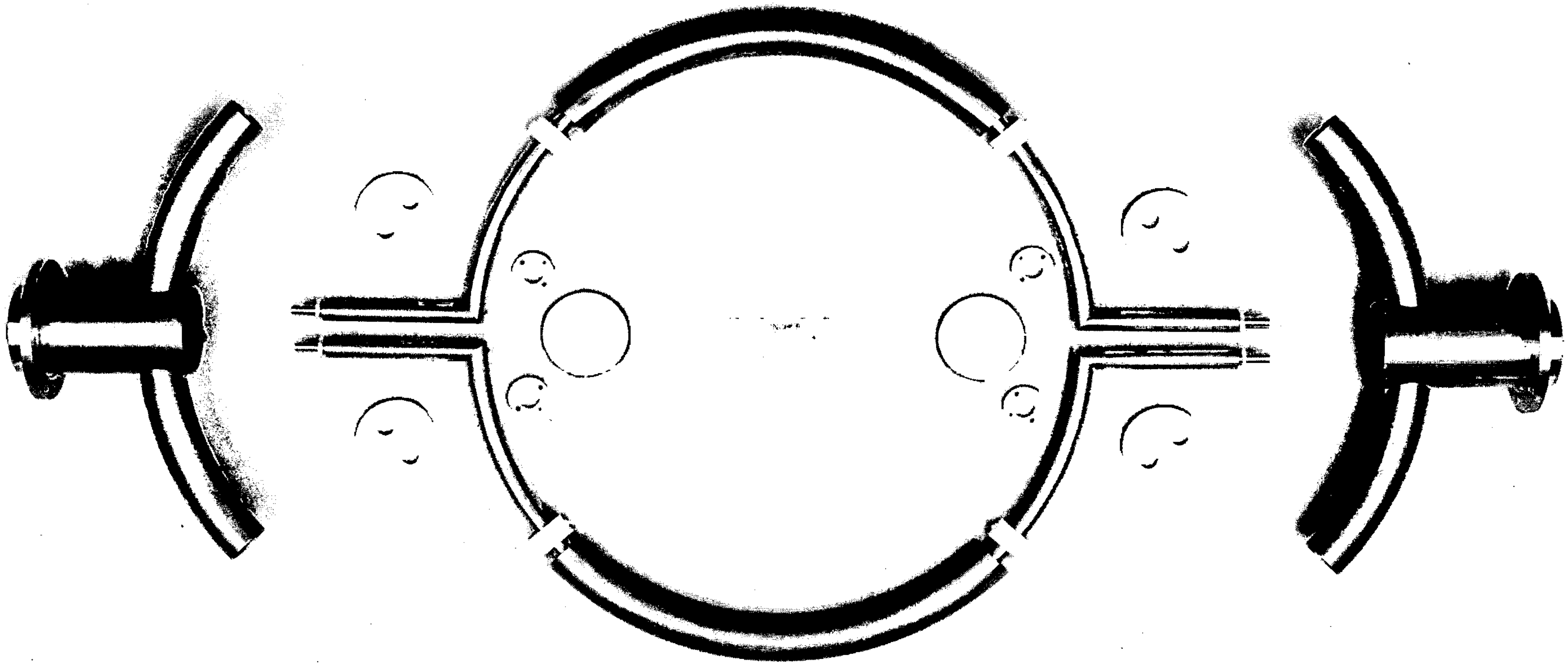

Figure 2. An Exploded View Showing the General Construction of the Four-Gap Shielded Loop Inductor. The Four Water Nozzles Can Be Seen at the Extreme Ends of the Center Conductors for Use in Water-Cooling the Loop.

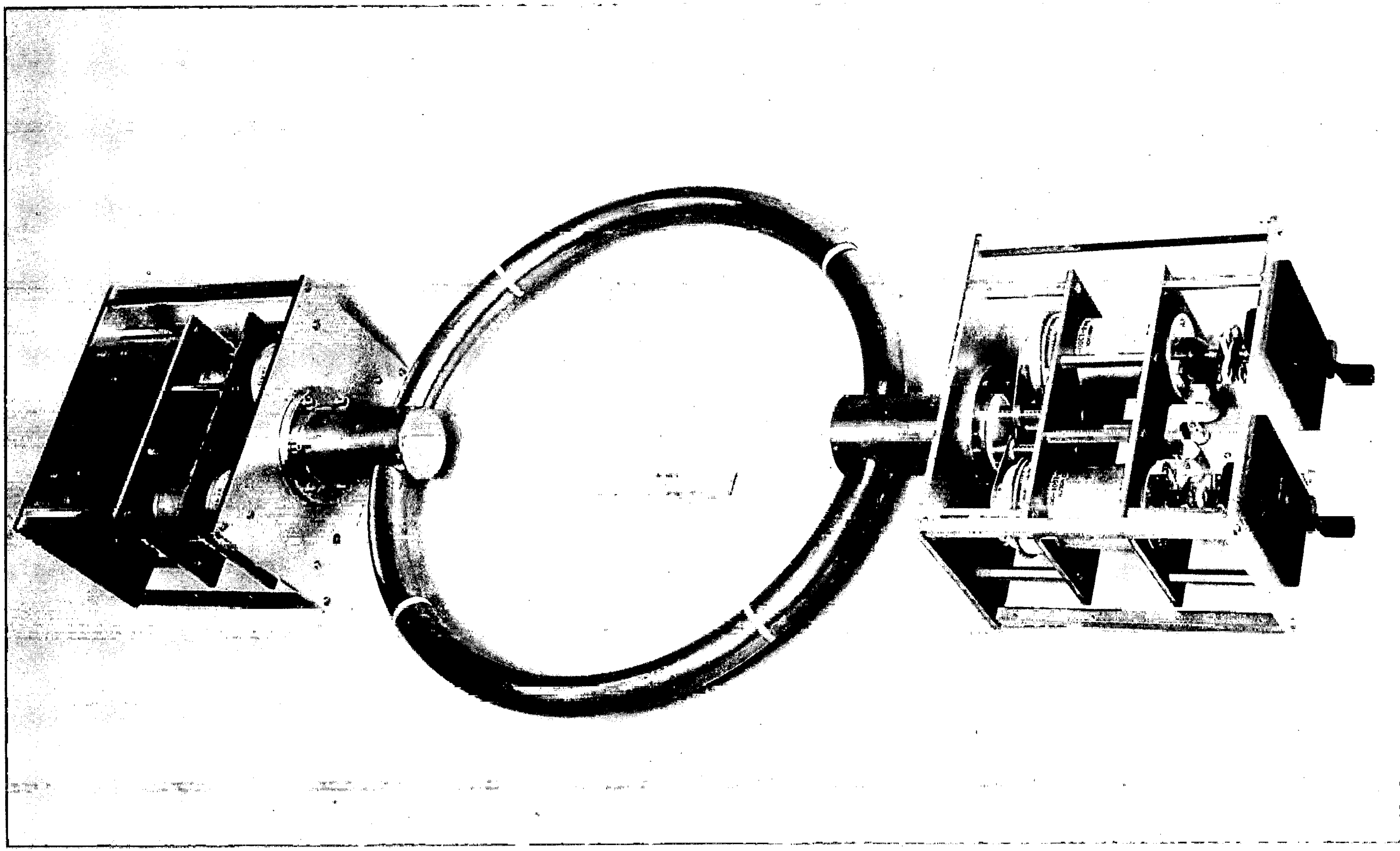

Figure 3. An Assembled View of the RF Magnetic-Field Generator Showing the Shielded-Loop Inductor and the Two Integral Matching Networks with Covers Removed.

The relationship between the magnetic field strength, H, in equation (2) and the loop current, I, is given by [7]

$$H = \frac{I}{d_1}, \quad A/m. \tag{3}$$

Thus for H = 50 A/m, and d_1 = 0.5 m, the loop current will be 25 A, requiring a single-source RF driving voltage of approximately 8000 V at 40 MHz [4].

2.3 The Loop-Inductor Matching Networks. The two balanced, tunable networks used with each of the loops provide for impedance matching between the loop inductor and driving generator over the frequency range 10 to 40 MHz. The circuit diagram of one of the two identical matching networks used with each loop is shown in Figure 4, and comprises vacuum variable capacitors C-1 and C-2, and inductor L-1. A separate

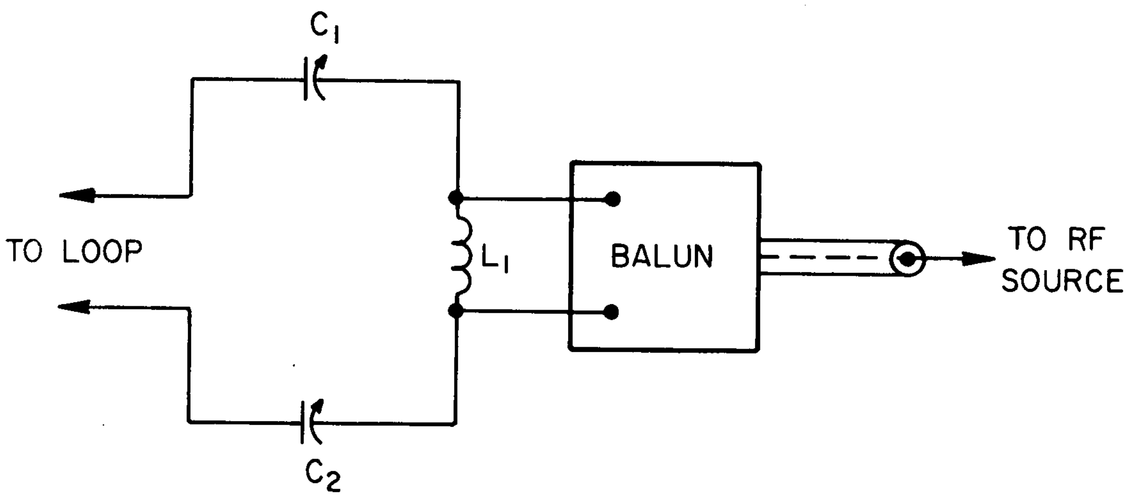

Figure 4. The Circuit Diagram of One of the Two Identical Matching Networks Used with the Shielded Loop Inductor.

balun transformer is also provided, as shown, between the 300-ohm balanced input to each network and its 75-ohm coaxial transmission line. The coaxial input circuits of the two matching networks are driven in parallel from a common source as shown in Figure 1. A close-up view of one of the matching networks is shown in Figure 5.

The loop inductor, and inductor L-1 in Figure 4, are tuned to resonance at the desired operating frequency by the capacitors, C-1 and C-2, each of which has a range of adjustment from 10 to 1000 pF for the large loop, and 5 to 500 pF for

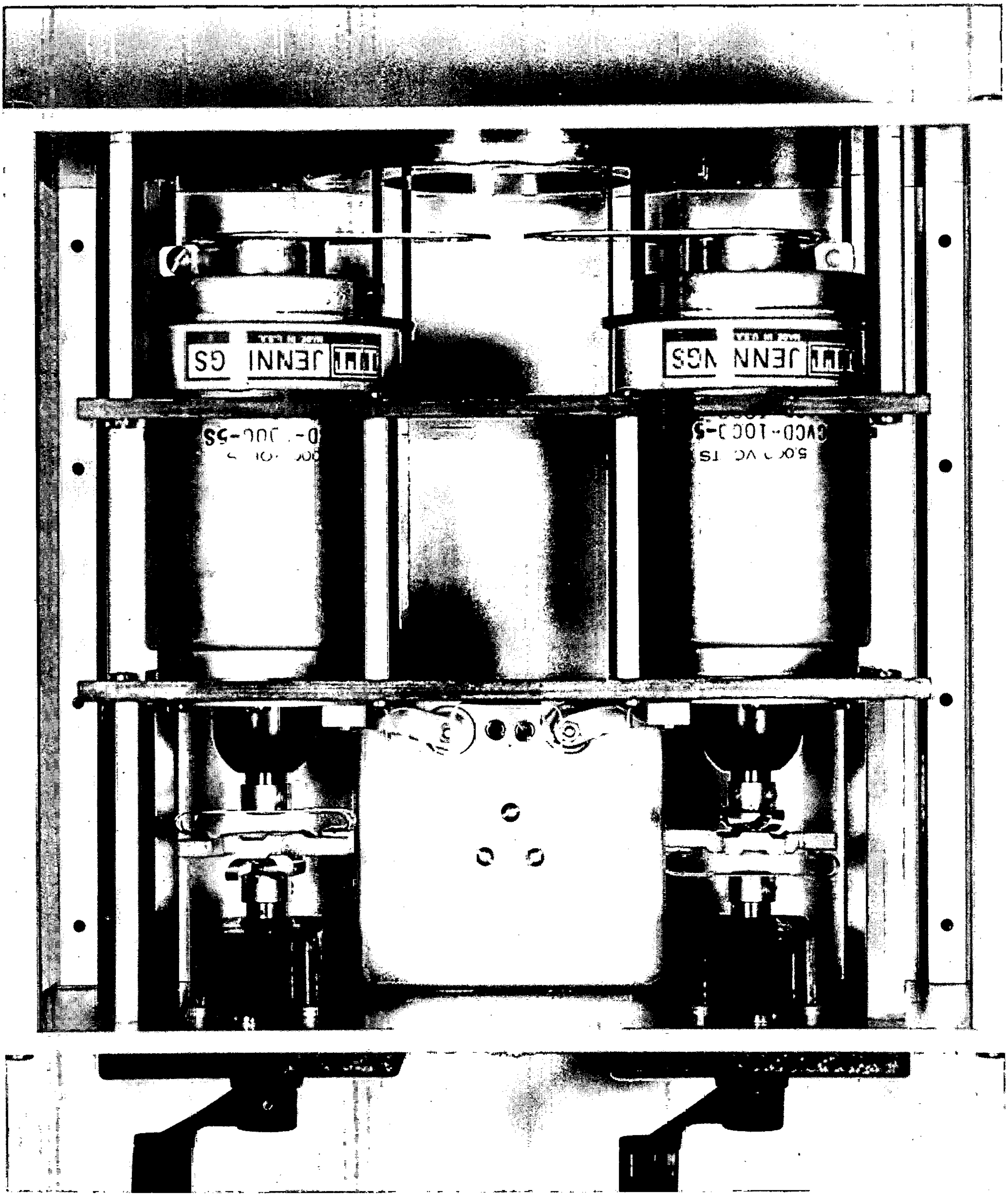

Figure 5. A View of One of the Tunable Loop-Inductor Matching Networks Showing the Two Vacuum Capacitors and the Shielded Balun Transformer.

the small loop. The balanced input impedance is determined by the value selected for inductor, L-1, in a manner exactly analogous to that employed when using a tapped, tuned tank circuit.

When properly resonated the input impedance, Z_{in}, is purely resistive and is given to a good approximation [8] by the following expression (provided $Q \geq 10$):

$$Z_{in} \simeq \frac{X_L^2}{R}, \quad \text{ohms,} \qquad (4)$$

where X_L is the reactance of the inductor, L-1, at the resonant frequency, and R represents half the total equivalent series loss resistance of the loop circuit, including conductor, dielectric, and radiation losses. The latter is assumed negligible as will be discussed later. This means that essentially all of the input RF driving power to the loop will be converted into heat and dissipated in the loop and associated circuitry.

2.4 The Vacuum Variable Tuning Capacitors. The vacuum variable capacitors used in the loop-inductor matching networks have the following advantages over conventional air variable capacitors for this type of use:

(a) a larger absolute capacitance as well as a larger range of capacitance adjustment (ratio of maximum to minimum capacitance) for a given physical size;

(b) a higher RF voltage breakdown rating;

(c) lower RF losses and heating and therefore a higher RF current rating. The RF current rating for a given frequency can be limited by either the RF heating, or by RF voltage breakdown resulting from the reactive voltage drop;

(d) a lower internal inductance, and therefore a higher self-resonant frequency.

2.5 The Balun Transformer [9]. The toroidal balun transformer used in each of the matching networks converts the 300-ohm balanced-network input impedance to a 75-ohm unbalanced coaxial drive. The balun has an RF power rating of one kilowatt continuous at 99 percent efficiency (.05 dB insertion loss). A view of the balun is shown in Figure 6. The winding arrangement is shown in Figure 7 and 8. Copper ribbon 2.5 mm wide by 0.3 mm thick is used which is the equivalent of No. 14 AWG (1.5 mm dia) copper wire in electrical conductivity in this frequency range and is much easier to wind physically. The balun is wound on a ferrite toroidal core approximately 60 mm O.D. x 35 mm I.D x 25 mm thick which has an initial relative permeability of approximately 40 for frequencies up to at least 40 MHz. The purpose of the core is to increase the common-mode rejection at the lower frequencies. The transformer has a measured common-mode rejection of approximately 30 dB over the frequency range 10 to 40 MHz.

The winding directions are important and are as shown in Figure 8. The common-mode currents, I_c, in the two transmission lines magnetize the core in the directions shown by the arrows. Since the magnetic flux produced by these currents in the two lines is in the same direction in the core, this results in a maximum common-mode inductance. The balanced-mode currents in the two sides of each transmission line are equal in magnitude and opposite in phase. They therefore produce very little, if any, magnetization of the core and hence no balanced-mode inductance. The core therefore has little, if any, effect on the two transmission lines operating in the balanced mode and serves only to attenuate the common-mode currents. As a result, there is little, if any, RF core loss in normal operation. The losses are essentially all in the copper windings, which helps to explain the high operating efficiency.

2.6 <u>The Water Cooling of the Inductors</u>. The loop inductors are designed to be water-cooled, since the measured RF driving power required to overcome circuit losses and produce a magnetic field of 50 amperes per meter is in the range from approximately 175 watts to over 500 watts over the operating frequency range 10 to 40 MHz. Water cooling is necessary for two reasons: (a) it reduces the effect of an increase in the ambient air temperature on the test results; and (b) it helps to stabilize the loop tuning which otherwise drifts appreciably as the loop heats up. The water flows through the interior of the loop center-conductor and so is essentially not in contact with the electrical part of the circuit. This is true except at points of entry and exit where the length of the water column is sufficient to minimize any shunting effect. Distilled water is used to minimize RF losses in the water, and to minimize corrosion of the copper tubing.

The water-cooling system used consists of a radiator and fan unit having a heat-transfer rating of 12.25 kg-cal/min based on a 2°C temperature difference between the inlet and outlet water. A motor-driven centrifugal water pump provides a water flow of approximately 10 liters/min which is more than sufficient to limit the temperature rise of the water to 2°C for a heat transfer of 500 watts (7.17 kg-cal/min) or less. A pressure-switch interlock is provided to turn off the transmitter in the event the water flow drops below a preset value during operation.

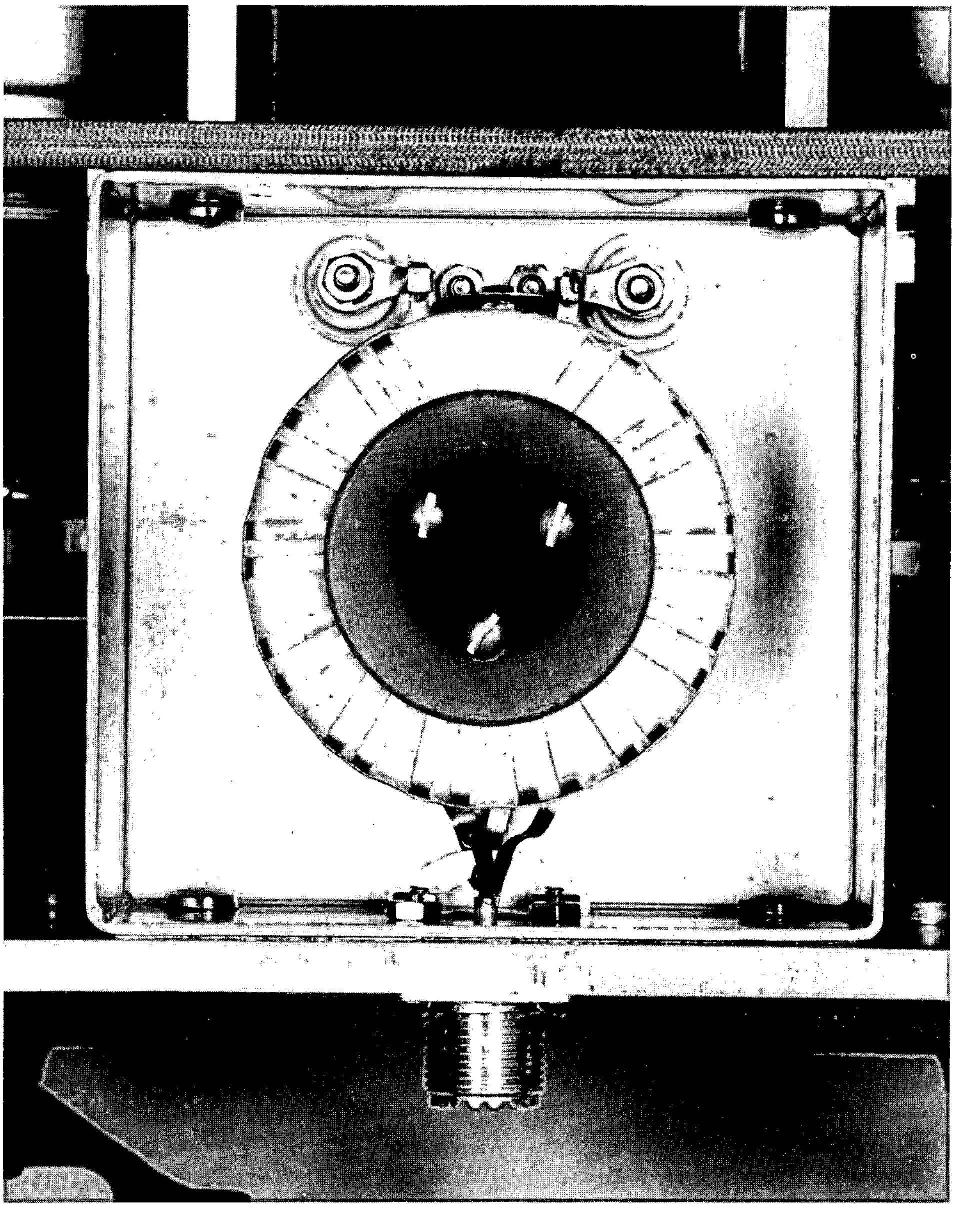

Figure 6. A Bottom View of One of the 75 to 300 Ohm Toroidal Balun Transformers Used in the Loop-Inductor Matching Networks.

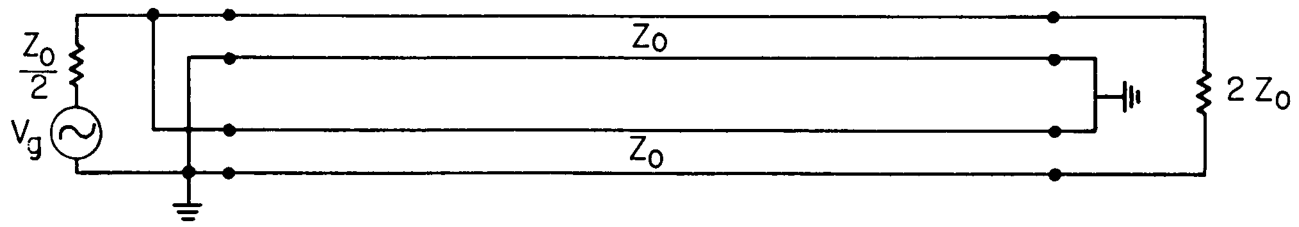

Figure 7. A Basic Balun Circuit Comprising Two Balanced Transmission Lines of Characteristic Impedance, Z_0. The Lines are Connected in Parallel at One End and in Series at the Other, Giving an Impedance Transformation Ratio of 4:1.

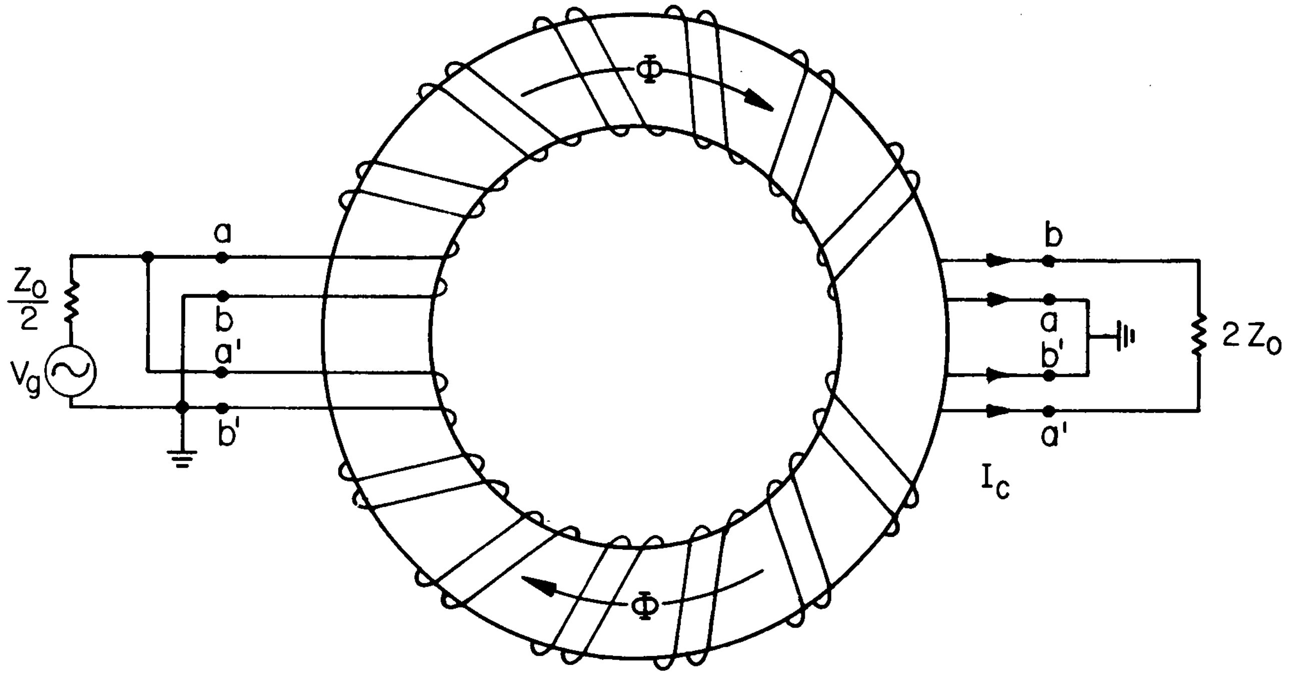

Figure 8. The General Method of Winding Used in the Toroidal Balun Transformer. The Basic Arrangement is the Same as that of Figure 7, Except that the Transmission Lines Have Been Wound on a Toroidal Core to Increase the Common-Mode Rejection at the Lower Frequencies.

3. THE RF ELECTRIC-FIELD GENERATOR

3.1 The Physical Characteristics of the Parallel-Plate Strip Lines. The RF electric-field generator of each of the two synthesizers consists of a balanced parallel-plate strip line. The larger of the two lines is fabricated from 1.5 mm thick aluminum sheets approximately 90 cm wide and spaced 70 cm apart. The line is approximately 90 cm in length along the straight portion, and tapers both in width and spacing over a distance of approximately 60 cm on the driven end as shown in Figure 9. The smaller of the two strip lines is also fabricated from 1.5 mm thick aluminum sheets which are approximately 60 cm wide and spaced 50 cm apart. This line is approximately 60 cm in length along the straight portion, and tapers both in width and spacing over a distance of approximately 35 cm on the driven end in a manner similar to that of the larger line. The tapered end of each strip line permits connecting the balanced RF feed line with a minimum of electrical discontinuity. Connection is made through two large feed-through bushings using steatite insulating cones.

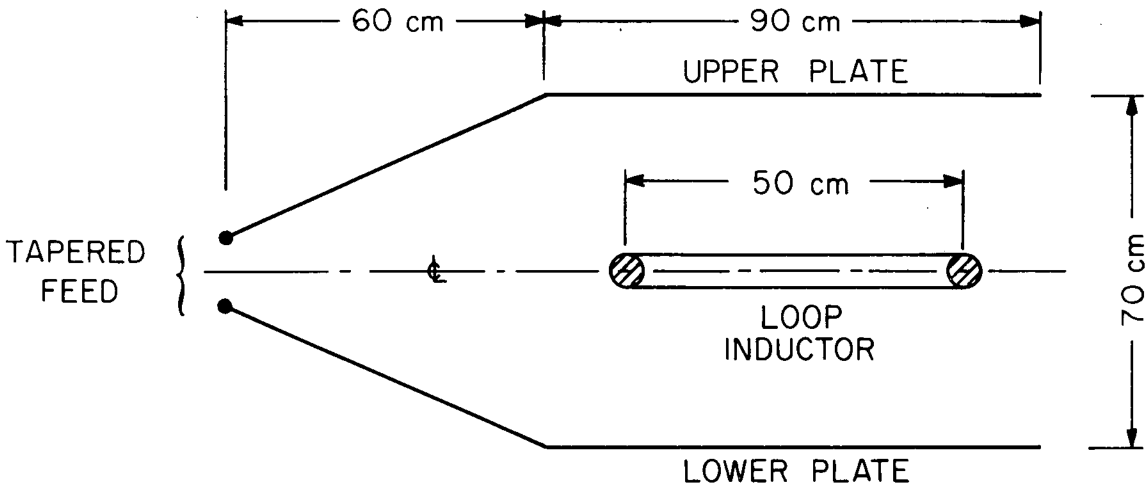

Figure 9. The General Arrangement of the RF Near-Field Synthesizer. The Loop Inductor is Located Midway between the Balanced Parallel Plates Normally in the Neutral Plane, but can be Tilted at Any Angle up to 60 Degrees.

These pass through a metal plate on one side of the shielded room in which the synthesizer is located and into the tunable matching unit which is fastened to the outside. A view of the strip line is shown in Figure 10.

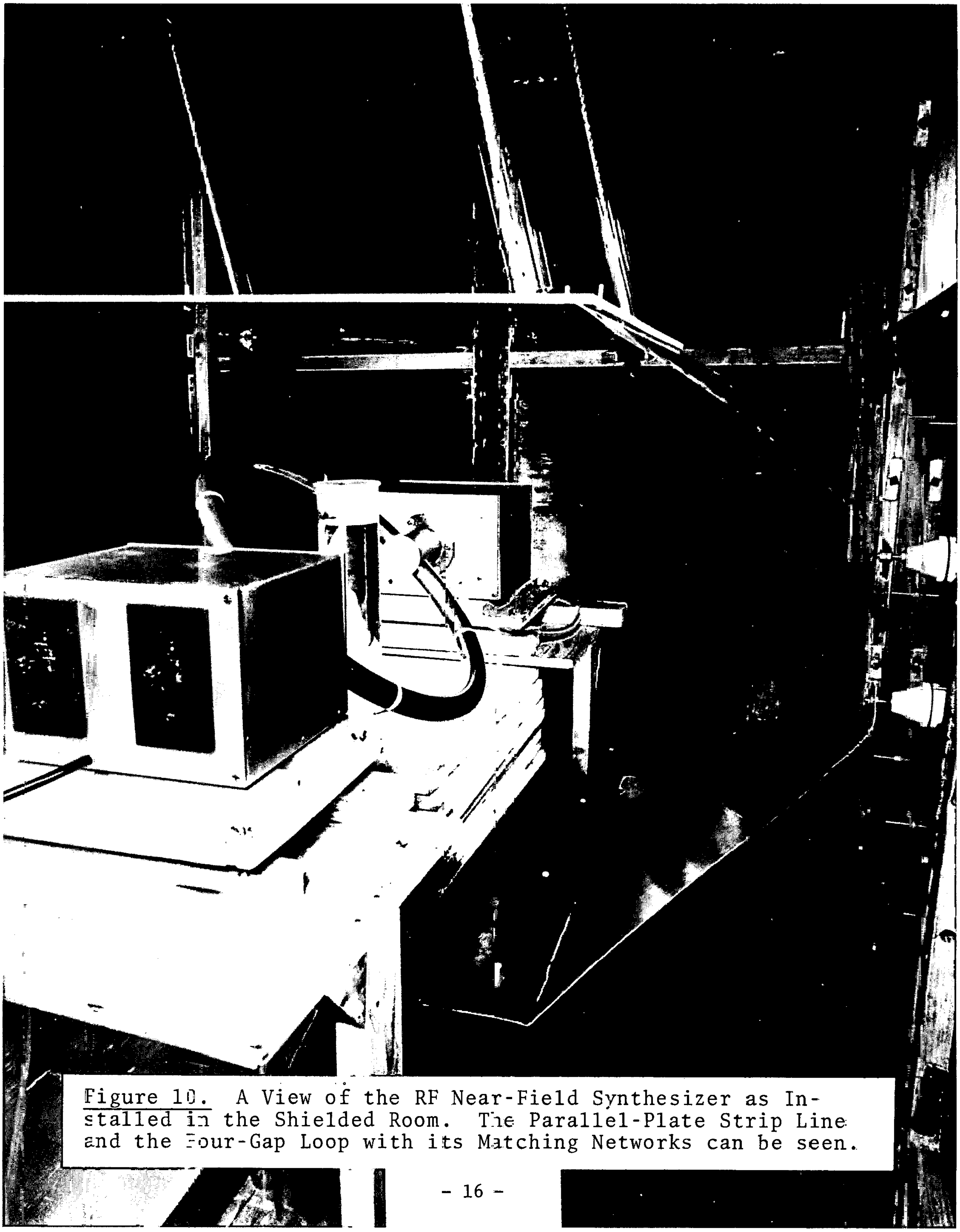

Figure 10. A View of the RF Near-Field Synthesizer as Installed in the Shielded Room. The Parallel-Plate Strip Line and the Four-Gap Loop with its Matching Networks can be seen.

3.2 The Parallel-Plate Matching Network. A balanced, tunable network is provided for impedance matching between the parallel plates and the driving generator. The network is housed in a large aluminum case 45 cm x 45 cm x 40 cm which is in turn fastened to the outside center of the shielded room in which the synthesizer is operated. Electrical connection is made to the parallel plates by means of the two large feed-through bushings previously mentioned. The size of the housing is dictated by the size of the tuning coils employed in order to obtain maximum Q and RF power-handling capability. A small muffin fan is used to exhaust air from a vent in the top side of the enclosure to facilitate cooling the inductors of the matching network. A matching air inlet is provided in the bottom of the enclosure to ensure proper air circulation.

The circuit diagram of the matching network is shown in Figure 11. The parallel plates are tuned to resonance at the

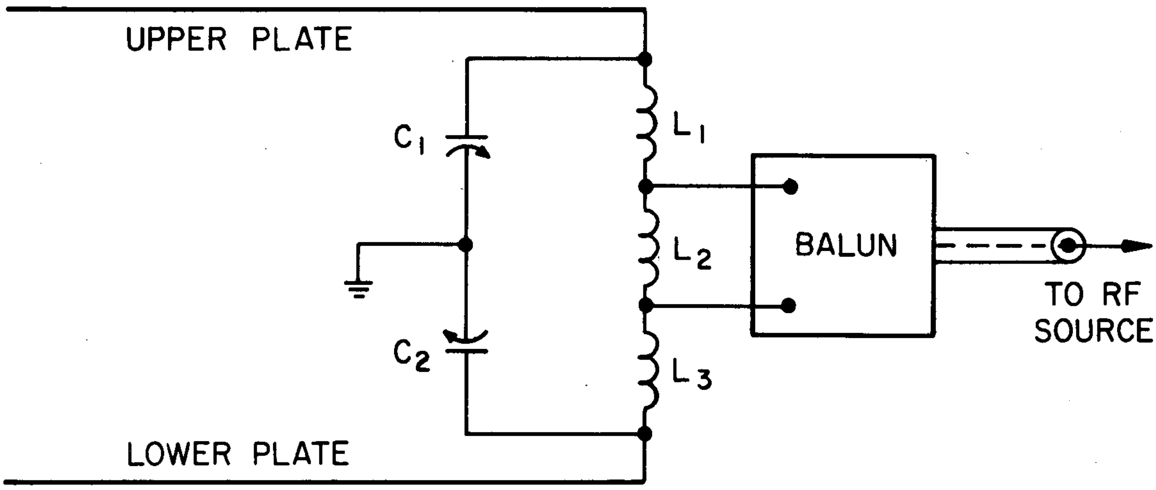

Figure 11. The Circuit Diagram of the Parallel-Plate Matching Network.

desired operating frequency by the balanced inductance comprised of L-1, L-2, and L-3. The two vacuum variable capacitors, C-1 and C-2, facilitate the tuning. Each has a range of adjustment from 6.5 to 50 pF. The input impedance is determined by the value selected for inductance L-2 in exactly the same manner as previously described for the magnetic-field generator, and can be determined from Equation (4), Section 2.3.

A toroidal balun transformer is used as shown in the circuit diagram to convert the 200-ohm balanced-network input impedance to a 50-ohm unbalanced coaxial drive. The transformer is similar to those used with the loop matching networks.

3.3 The Electrical Characteristics of the Parallel-Plate Strip Line. The "unwanted" magnetic field produced by the parallel plates was found to be negligibly small for the plate size, frequency, and the magnitude of the electric field, E, being generated. No special design was undertaken to minimize this "unwanted" magnetic field as was done in the case of the loop inductor. Although, it would have been possible to have reduced the magnetic field in the central portion of the parallel plates by a factor of at least three, if necessary, by driving the plates simultaneously [10] at both ends instead of at one end.

An RF driving power of between approximately 150 and 400 watts is required over the frequency range of 10 to 40 MHz to produce an electric field strength of 5000 volts per meter between the plates as required by the sponsor. This is the power required to supply the conductor and dielectric losses of the parallel plates and associated circuitry, the radiation losses again being negligible because of the mode of operation, as in the case of the loop inductor. Because of the surface area involved in the parallel plates, their losses are minimal. Little temperature rise was observed, and no cooling was found necessary. Most of the loss was found to be in inductors L-1, L-2, and L-3 (Figure 11).

4. THE COMPLETE SYNTHESIZER UNIT

4.1 A General Description. In the completed RF near-field synthesizer the single-turn loop inductor of the magnetic-field generator is mounted midway between and parallel to the two balanced plates of the electric-field generator as shown in Figure 9. The normal position of the loop inductor is thus in the neutral plane between the plates, although the loop can be operated at any angle to the horizontal of up to 60 degrees. This provides the means for adjusting the relative spatial orientation between the electric and magnetic field vectors as specified by the sponsor. The electric and magnetic coupling between the two field systems has been minimized because of the balanced symmetry employed in the excitation of both the loop inductor and the parallel plates, as well as their relative physical orientation. This was confirmed during the acceptance tests in which no observable cross coupling could be detected even with power inputs of up to one kilowatt to either or both the field generators for any angular position of the loop inductor up to 60 degrees from the horizontal.

4.2 The Effect of the Shielded Room. The near-field synthesizer is installed and operated inside of a doubly-shielded copper room approximately 2.0 m wide x 3.0 m long x 2.0 m high. The RF power required to drive either the electric- or magnetic-field generator has been found to be the result mainly of losses within the generators and matching networks themselves (i.e. metallic and dielectric losses in the inductors, capacitors, parallel plates, etc.). Radiation losses are, for the most part, nonexistent because of operation of the generators inside a copper-shielded room having a shielding efficiency of at least 60 dB. Coupling between each field generator and the interior walls of the screened room has been found to be very loose and is essentially reactive. Very little resistance is coupled back into the field generators from the room walls, since: (a) the copper walls of the room are low-loss; (b) the physical dimensions of the generators are small compared to the room dimensions; and (c) the frequency of operation is well below the lowest possible self-resonant frequency of the shielded room operating as a low-loss rectangular cavity resonator. For this room the lowest possible self-resonant frequency [11] is approximately 80 MHz.

4.3 The RF Excitation of the Field Generators. The two field generators are driven or excited as shown in the block diagram of Figure 12. Separate, synchronized, transmitters are used, each of which is composed of a 100-watt driver transmitter followed by a 100-watt frequency-doubling amplifier (the latter being used only when an operating frequency of 40.68 MHz is desired). These units are in turn followed by a one-kilowatt RF power amplifier as shown. Internal relays connect the doubler amplifier and the power amplifier straight-through when their AC power is turned off, permitting operation with the 100-watt driver transmitter during preliminary tune-up, if desired, without reconnecting the coaxial cables. Synchronization is achieved by operating both 100-watt driver transmitters from the same crystal oscillator. Separate frequencies can be easily used for each transmitter if for any reason it is desired. Reflectometers are provided, as shown, to facilitate tuning the two systems. It is found advantageous to first tune the loop-inductor and the parallel plates so as to have the correct input impedance, using one of the new RF vector-impedance meters as discussed further in Section 7.1. Interlocking relay contacts are provided in each reflectometer to turn off the transmitter in the event the reflected power exceeds a preset value during operation.

Five special plug-in quartz crystals were supplied by NBS for the oscillator stages of each of the two 100-watt driver transmitters. These crystals are in the frequency range 5.0 to 7.5 MHz. By proper frequency multiplication in the transmitters these crystals can be used to produce 25 different output frequencies in the range from 5 to 45 MHz as shown in Table I. Additional crystals may be added at anytime, as desired, up to a total of 10 (the maximum number of crystal positions provided in each transmitter). A frequency tolerance of ± 0.001 percent and a standard crystal load capacitance of 32 pF should be specified when ordering additional crystals.

4.4 The Phase Difference Between E and H. In the far field the electric and magnetic fields are in time phase with each other, while in the near field they approach a 90° phase difference, in the limit, as the source is approached. This means that in practice the phase difference between E and H will always lie somewhere in the range between 0° and 90°.

There are a number of ways by which the phase difference between the E and H fields produced by the synthesizer can be adjusted. These include: (a) the use of adjustable pi-type phase-shift networks [12] in the output of one or both transmitters; or (b) a slight detuning of the oscillator and/or buffer stages of one or both driver transmitters to produce the desired phase shift.

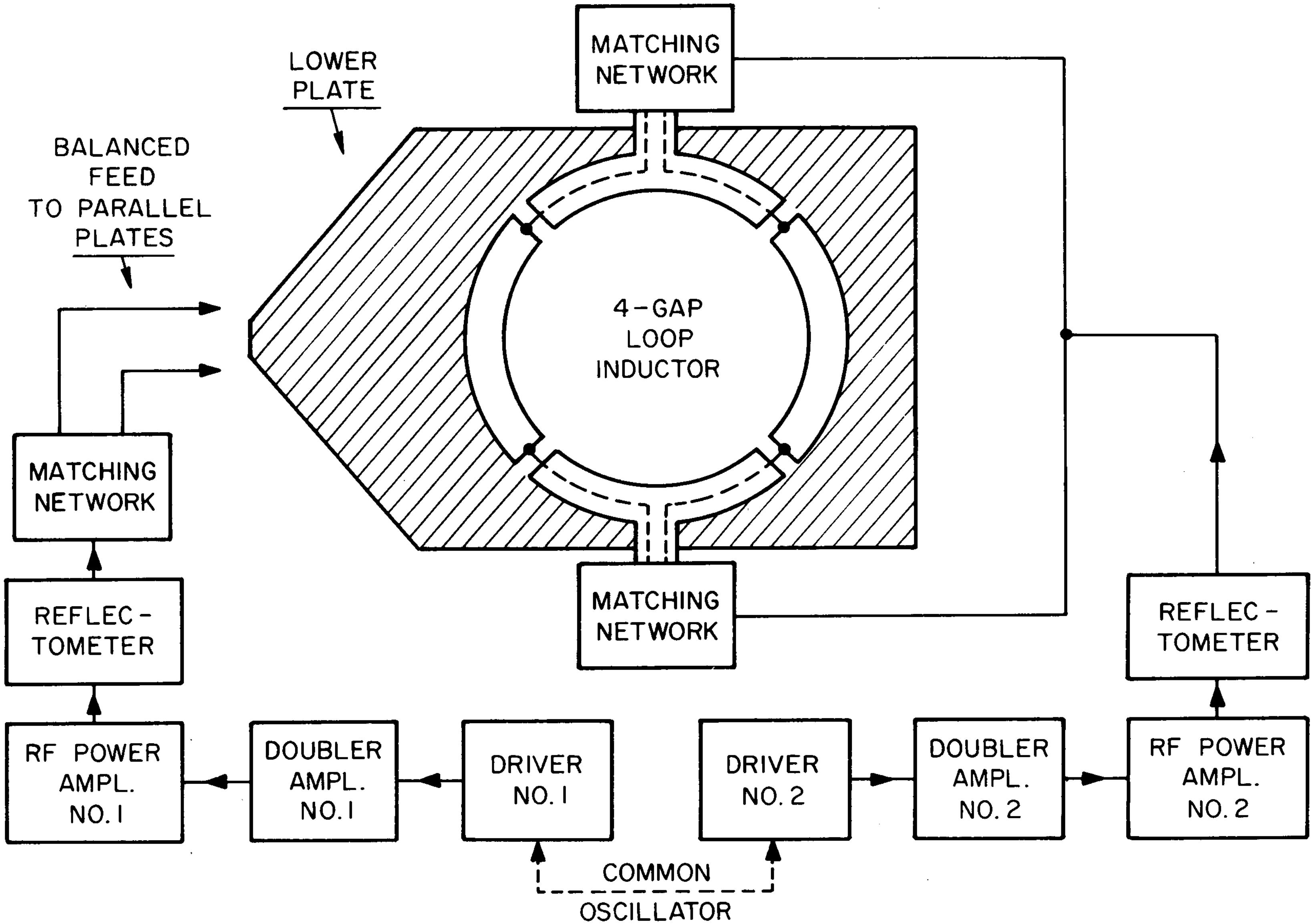

Figure 12. A Block Diagram of the Complete RF Near-Field Synthesizer Showing All of the Principal Components Including the RF Power Sources.

The difficulty comes about in accurately measuring and monitoring this phase shift. Unknown phase shifts are introduced by the probes used to sample the fields, and by the transmission lines used to carry the probe signals to the points at which they will be measured. It appears that some additional work will be required in order to develop an accurate method for determining the time-phase difference between the E and H fields of the synthesizer.

4.5 The RF Exposure Capability. The electric-field generator can produce a fairly pure (high-impedance) E field of up to 5,000 volts per meter over the frequency range 10 to 40 MHz. The magnetic-field generator can produce a fairly pure (low-impedance) H field of up to 50 amperes per meter over the same frequency range. The two fields can be adjusted essentially independently in amplitude. As a result, the ratio of the magnitude of the electric field to that of the magnetic field can be adjusted to any value between roughly 40 and 4000 (i.e. from approximately one tenth the free-space value of the wave impedance of a uniform plane wave (377 ohms) to ten times this value). The phase difference between E and H can be adjusted for angles up to 90 degrees, within the limitations previously discussed, and the relative spatial orientation for angles up to 60 degrees in order to simulate various near-field configurations. NBS has specified that from 10 to 40 MHz the total inaccuracy of electric and magnetic-field-strength generation is $\pm$ 10% of the field strength. An RF driving power of up to one kilowatt is required for each field system depending upon frequency and the field level used.

5. CONCLUSIONS

The RF radiation-exposure facility described in this report will enable researchers to independently generate hazard-level electric and magnetic fields for use in conjunction with their non-ionizing RF radiation-exposure programs being carried out in the frequency range 10 to 40 MHz. This RF near-field synthesizer, in conjunction with the electric, and magnetic near-field probes recently developed at NBS [13], will also enable researchers to evaluate any near-field effects encountered in connection with their studies of RF biological hazards. The synthesizer can also be used for the calibration and intercomparison of other similar probes.

The synthesizer can be used to generate a fairly pure (high-impedance) electric field and a fairly pure (low-impedance) magnetic field over the above frequency range. These two fields can be adjusted essentially independently over wide ranges of magnitude, phase difference and relative spatial orientation in order to simulate various near-field configurations. The maximum RF driving power required is one kilowatt for each field system, depending upon the frequency and field level used.

The recent discovery at NBS and elsewhere of the major roll played by the magnetic component of the field in the area of RF biological hazards to humans in this frequency range [14], points up the need for suitable instrumentation for further evaluating this effect.

Previous research in RF biological hazards has been largely limited to the use of plane-wave fields for making clinical studies. These new devices will allow researchers to investigate any near-field effects that may occur at high field levels.

6. RECOMMENDATIONS

Consider ways to further reduce the tuning drift of the synthesizers including: (a) water-cooling of the vacuum tuning capacitors; (b) the use of DC voltage feedback from the reflectometer to adjust the frequency of the crystal oscillator; and (c) the use of a purer form of copper in the construction of the loops to increase their electrical conductivity; resulting in reduced RF losses, heating, and driving power by as much as a factor of two. Oxygen-free high-conductivity (OFHC) copper is ideal but is difficult to procure in the tubing sizes required, except in production quantities ordered directly from the mill.

Develop improved methods for accurately measuring the phase difference between the electric and magnetic fields generated by the synthesizer. Uncertainties introduced by the field-sampling probes and the associated transmission lines need to be resolved.

Analyze various methods to determine the RF power absorbed by biological samples placed in the synthesizer. One method might be based on the change in reflected power produced by the sample; a second on the temperature rise vs. time of the test sample; etc. Methods of tuning and adjusting will also probably be involved.

It appears that the tuning range of the small synthesizer can be extended upward to 50 MHz by making minor modifications in the loop-inductor straps in the two matching units. It would also be necessary to reduce the length of the small parallel-plate strip line by 25 percent and to make minor tuning modifications in the two doubler amplifiers and in the two power amplifiers.

Develop improved techniques for using the synthesizer to produce "standard" electric and magnetic fields for the accurate calibration and intercomparison of the near-field probes previously discussed. It may be possible to establish the value of these fields in terms of the physical dimensions of the synthesizer together with the value of RF input power being used.

7. APPENDIX---OPERATING PROCEDURE

7.1 Synthesizer Tuning Data. Tuning information for the large synthesizer for each of seven frequencies from 10 to 30 MHz is contained in Table II. Tuning information for the small synthesizer for each of six frequencies from 20 to 40.68 MHz is contained in Table III.

7.1.1 Loop Tuning. The approximate dial settings for the loop-tuning capacitors, C-1 and C-2 (Figure 4), for the various frequencies are given in the 2nd column in both tables. The correct size of the matching inductor, L-1, in each case is given in the 3rd column.

7.1.2 Parallel-Plate Tuning. The approximate dial settings for the tuning capacitors, C-1 and C-2 (Figure 11), for the various frequencies are given in the 5th column in both tables. The correct size of the inductors L-1 and L-3 (which are identical in size) is given in the 6th column. The correct size of the matching inductor, L-2, in each case is given in the last column.

7.1.3 Additional Frequencies. For frequencies other than those shown in the tables, the tuning data can be interpolated to determine the approximate sizes of the various inductors, and the tuning-capacitor dial settings.

7.1.4 Adjusting the Input Impedance. The use of a vector-impedance meter or a network analyzer is recommended when making the preliminary adjustment of the input impedance of either the loop or parallel plates to approximately 50 ohms in each case. After this preliminary adjustment, the loop or plates should be operated at a low RF power level from the transmitters of from 10 to 20 watts, until a power match has been achieved as indicated by the reflectometers (zero reflected power). See Section 7.2 for additional tuning details.

7.2 Overall Tuning Procedure (see Figure 12 for block diagram).

(a) Set up and tune the loop and parallel plates to the desired operating frequency in accordance with Section 7.1 and TABLES II and III.

(b) Turn the AC power ON to the loop-inductor water pump and to the fans on the two DRIVER TRANSMITTERS and the parallel-plate tuning unit.

(c) Leave the AC power turned OFF to both DOUBLER AMPLIFIERS and both POWER AMPLIFIERS. This leaves these units with their coaxial inputs connected straight through to their outputs when not energized.

(d) Select the desired operating frequency and corresponding CRYSTAL switch position indicated in TABLE I. Turn the AC power ON to both DRIVER TRANSMITTERS and tune them for an RF power output in the range from 10 to 20 watts in accordance with their instruction manual.

(e) To synchronize both DRIVER TRANSMITTERS to the same frequency: set the CRYSTAL switch of Unit No. 14897 to the switch position indicated in TABLE I corresponding to the desired frequency; set the CRYSTAL switch of Unit No. 14849 to switch position "0." Should it ever be desired to operate the DRIVER TRANSMITTERS at different frequencies, set their respective CRYSTAL switches to the switch positions indicated in TABLE I corresponding to the desired frequencies.

(f) When it is desired to operate at 40.68 MHz, the two DRIVER TRANSMITTERS should be first tuned to the half frequency of 20.34 MHz. The two DOUBLER AMPLIFIERS should then be turned ON and tuned for an output in the range of 10 to 20 watts at 40.68 MHz, adjusting the output of the DRIVER TRANSMITTERS as required to give this power.

(g) With an incident power not exceeding 20 watts, tune the loop and parallel plates for zero reflected power on their respective reflectometers. It will be found most convenient to achieve this by tuning one of the loop capacitors and one of the parallel-plate capacitors. Afterwards, any difference in dial readings should be distributed among the other capacitors until all four loop capacitors have identical dial readings, and both parallel-plate capacitors have identical readings, and the reflected power in both cases is zero.

(h) Recheck the tuning of the two DRIVER TRANSMITTERS and the two DOUBLER AMPLIFIERS (if in use) in accordance with their respective instruction manuals. Increase the power input to the loop and parallel plates to approximately 50 watts by increasing the DRIVE setting of the DRIVER TRANSMITTERS. Recheck the tuning of all units, and then increase the power level slowly to 100 watts. Recheck the tuning of all units occasionally. At this power level some drifting of the loop and parallel-plate tuning will be noticed as the units warm up. When the reflected power exceeds 10 percent reduce it to zero by making a slight readjustment of one of the tuning capacitors. When this readjustment exceeds one dial division, it should be redistributed among the other capacitors in order to keep the dial readings identical (see previous paragraph).

(i) When a power level greater than 100 watts is desired, it will be necessary to use the POWER AMPLIFIERS. Reduce the DRIVE setting of the DRIVER TRANSMITTERS to zero and detune the OSCILLATOR dial slightly until the FINAL-AMPLIFIER PLATE CURRENT of the DRIVER TRANSMITTERS is reduced to zero.

(j) Before proceeding repeat paragraphs (a) through (i). Turn the AC power ON to the POWER AMPLIFIERS. Retune the OSCILLATOR slowly until the 1-KW POWER-AMPLIFIER PLATE CURRENT is approximately 100 m.a. Tune the POWER AMPLIFIERS for maximum power output, readjusting the drive as required to produce not over 100 watts output. Recheck the tuning of all units, and readjust the loop and parallel plates for zero reflected power.

(k) The system is now ready for use at RF power levels greater than 100 watts. The power output is increased by increasing the DRIVE control of the DRIVER TRANSMITTERS. As the power output is increased, the POWER AMPLIFIERS should be retuned to maximize their output. Periodically recheck the tuning of all units, and readjust the loop and parallel plates for zero reflected power.

(l) Before turning the AC power OFF to either the POWER AMPLIFIERS or the DOUBLER AMPLIFIERS the RF drive should first be reduced to zero. This is to prevent arcing of the internal RF relay contacts when they open, increasing their life and preventing welding or pitting of the contacts.

(m) After the POWER AMPLIFIERS have been turned OFF, paragraphs (i) and (j) should be followed before the POWER AMPLIFIERS are turned ON again.

(n) The OPERATING FREQUENCY of the SYNTHESIZER can be easily verified at any time by the use of a conventional FREQUENCY COUNTER. The COUNTER should be set up along side the screen room near the open door. A short piece of wire should be connected to the INPUT TERMINAL of the COUNTER to act as an ANTENNA to pick up sufficient signal to ensure proper operation of the COUNTER.

TABLE I

OPERATING FREQUENCIES FOR THE 100-WATT DRIVER TRANSMITTERS USING THE 5 CRYSTALS SUPPLIED BY NBS

Operating Frequency (MHz)	Crystal Frequency (MHz)	Xtal. Switch Position	Multiple (X)
5.000	5.000	1	1
6.250	6.250	2	1
6.666	6.666	3	1
6.780	6.780	4	1
7.500	7.500	5	1
10.000	5.000	1	2
12.500	6.250	2	2
13.333	6.666	3	2
13.560	6.780	4	2
15.000	7.500	5	2
15.000	5.000	1	3
18.750	6.250	2	3
20.000	6.666	3	3
20.340	6.780	4	3
22.500	7.500	5	3
20.000	5.000	1	4
25.000	6.250	2	4
26.666	6.666	3	4
27.120	6.780	4	4
30.000	7.500	5	4
30.000	5.000	1	6
37.500	6.250	2	6
40.000	6.666	3	6
40.680	6.780	4	6
45.000	7.500	5	6

TABLE II LARGE SYNTHESIZER

LOOP TUNING DATA (see Fig. 4)

Freq.	C_1, C_2	L_1(*)
(MHz)	(Rev.)	(length)
10	2-72	7"
13.56	5-49	5"
15	6-12	5"
20	7-34	4"
25	7-94	4"**
27.12	8-12	4"**
30	8-37	4½"

PARALLEL-PLATE TUNING DATA (see Fig. 11)

Freq.	C_1, C_2	L_1, L_3	L_2(*)
(MHz)	(Rev.)	(½" Tubing)	--
10	0-65	3 turns 6½" dia	1 turn 3" dia
13.56	0-20	2 turns 6½" dia	1 turn 2½" dia
15	3-85	2 turns 6½" dia	1 turn 2" dia
20	0-45	2 turns 3½" dia	1 turn 1½" dia
25	2-52	1 turn 4" dia*	U-strap 5" c-c
27.12	1-83	1 turn 2½" dia*	U-strap 5" c-c
30	5-55	U-strap 4¾" c-c*	U-strap 4" c-c

NOTES

* 3/4" strap width
** 1" strap width
c-c center-to-center strap length

TABLE III SMALL SYNTHESIZER

LOOP TUNING DATA (see Fig. 4)

Freq.	C_1, C_2	L_1(*)
(MHz)	(Rev.)	(length)
20	4-03	4⅝"
25	6-73	"
27.12	7-45	"
30	8-19	"
35	9-10	"
40.68	9-70	**

PARALLEL-PLATE TUNING DATA (see Fig. 11)

Freq.	C_1, C_2	L_1, L_3	L_2(*)
(MHz)	(Rev.)	(½" Tubing)	--
20	3-17	3 turns 3½" dia	1 turn 1½" dia
25	1-39	2 turns 3½" dia	U-strap 5" c-c
27.12	3-76	2 turns 3½" dia	U-strap 5" c-c
30	1-58	1 turn 4½" dia	U-strap 4" c-c
35	3-75	1 turn 3½" dia	U-strap 4" c-c
40.68	2-10	U-strap 3¾" c-c*	Str. Strap 2¾" c-c

NOTES

*	3/4" strap width
**	Two Q-2 ferrite toroidal cores (1 1/4" O.D. x 3/8" thick) were added in the "U" bend.
c-c	center-to-center strap length

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