**Quarterly Progress Report
on
RESEARCH AND INVESTIGATION LEADING TO METHODS
OF GENERATING AND DETECTING RADIATION IN THE
100 TO 1000 MICRON RANGE OF THE SPECTRUM**

Contract No. AT(11-1)-392

UNITED STATES ATOMIC ENERGY COMMISSION

ULTRAMICROWAVE SECTION
ELECTRICAL ENGINEERING RESEARCH LABORATORY
ENGINEERING EXPERIMENT STATION
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QUARTERLY PROGRESS REPORT

on

RESEARCH AND INVESTIGATION
LEADING TO METHODS OF
GENERATING AND DETECTING
RADIATION IN THE
100 TO 1000 MICRON WAVELENGTH
RANGE OF THE SPECTRUM

Contract No. AT(11-1-392)
Quarterly Report No. 7

by

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Urbana, Illinois

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1. INTRODUCTION - P.D. Coleman

1.1 Preface

This is the seventh quarterly report for Contract No. AT(11-1)-392 on "Research and Investigation Leading to Methods of Generating and Detecting Radiation in the 100 to 1000 Micron Wavelength Range of the Spectrum." This report covers the period 1 September 1957 to 1 December 1957.

1.2 Purpose

The purpose of this research is twofold:

- a) To uncover new principles or techniques from which a source of high pulsed power for the 100-1000 micron wavelength range of the spectrum can be developed. Ideally it is desirable that the source will possess a line spectrum.
- b) To investigate suitable detecting and measuring techniques for evaluating and using the radiation as a diagnostic tool for physical research.

2. GENERAL FACTUAL DATA - P.D. Coleman

2.1 Approach to the Generation Problem - Frequency Multiplication with a Non-Linear Element

The generation of electromagnetic radiation in the wavelength range 0.1 to 3 millimeters is as yet an unsolved problem. Moreover, even an idea that might lead to a prime source of radiation has yet to be suggested as far as this author is aware. This does not mean that research towards a source is not possible or fruitful at the present time,

It is well known that non-linear effects lead to the generation of harmonic and/or subharmonic frequencies. A number of physics phenomena show strong non-linear properties in the millimeter wavelength range, for example: (1) a silicon crystal rectifier, (2) a field emitter, (3) the magnetization of a ferrite, (4) a gas discharge, (5) an electron beam, etc. If the appropriate circuits or experimental arrangements incorporating these elements could be devised, and could be driven, for example, by a high power level eight millimeter wavelength electron tube, there are reasons to believe that low millimeter and submillimeter wavelength signals could be produced.

The synthesis of a non-linear circuit does not appear to be an easy task. What is ideally desired is an arrangement that can be driven at a frequency f_0 but which has dissipation only at a given frequency nf_0 , thereby achieving a gain of one in multiplying from f_0 to nf_0 . It is doubtful if this ideal circuit can be synthesized, but there is every reason to believe that the dissipation at a given harmonic frequency could be accentuated over all others. Circuits presently used--for example, one employing a silicon crystal--give a second harmonic power 15 to 20 db down from the fundamental drive power, the third harmonic power 25 to 30 db down, etc. It has not been demonstrated that these circuits are anywhere near optimum nor that conversion gains far greater than those presently obtained are theoretically possible.

It should be pointed out that a study of the non-linear element alone is not sufficient. For example, consider a field emitter whose law is $i = A \exp(-B/e)$. It is an elementary numerical problem to compute i versus e and to determine the Fourier series expansion coefficients for i under

period voltage excitation e . The problem to be solved is how to extract the maximum power at a specified harmonic frequency nf_0 . This later problem requires some sort of input coupling circuit from a generator at frequency f_0 and an output coupling circuit at frequency nf_0 to a load. Just how to make these coupling circuits optimum is the heart of the problem and one which appears to have no straightforward solution.

The present program being followed by the Ultramicrowave Group is based entirely on frequency multiplication using a non-linear element. Our major effort has been on (1) silicon crystal multipliers for achieving low power level CW millimeter signals for bench testing and development of components, and (2) megavolt electronics electron beam multipliers for producing high pulsed power level signals. More recently, work has been initiated on field emitter multipliers and plans are underway to investigate gas discharge and ferrite multipliers. All these attacks on the generation problem have in common the task of synthesizing an optimum non-linear circuit with maximum frequency conversion from f_0 to nf_0 .

2.2 Bunched Megavolt Beams as Non-Linear Elements for Use in Megavolt Electronics

A schematic drawing of a megavolt electronics millimeter wave generation system, using an electron beam as a non-linear element for frequency multiplication, is shown in Fig. 1. In this system, a high power microwave tube source at frequency f_0 drives a relativistic electron bunching accelerator, called a REBATRON, which converts a low voltage DC beam into a bunched megavolt beam containing high current harmonic frequencies of the driving source. This harmonic beam, in turn, drives a coupling device which converts a part of the beam kinetic energy into RF energy at frequency nf_0 .

A program on megavolt electronics, as seen from Fig. 1, involves three phases: (1) the production and evaluation of the bunched megavolt beam, (2) the study of beam coupling structures, and (3) the development of detectors and measuring components.

The problem of creating a high energy bunched electron beam has been initially solved in a very compact relativistic electron accelerator and buncher, called a REBATRON, which is illustrated in Fig. 2. This device consists of a single TM_{010} mode microwave cavity driven by a high power magnetron. A simple prebunching system is used to inject electrons into the accelerator. This system consists of a Pierce gun, modulating cavity, and drift distance arranged to give the entrance beam a desirable velocity-phase relationship to achieve good bunching in the accelerating cavity.

FIGURE 1 MEGAVOLT ELECTRONICS SYSTEM

FIGURE 2 REBATRON STRUCTURE

Theoretical calculations have given a computed harmonic content in the exit beam of appreciable value to as high as the 1000th term in the Fourier series representation of the current. Furthermore, the velocity spectrum of the accelerated electrons is sufficiently peaked that the beam can be quite accurately represented as a traveling current wave of the form

$$i(t, z) = \sum_s I_s \cos 2\pi s f_0 (t - z/v) \quad (1)$$

where

$$I_s \approx 2 I_0$$

and

$$v \approx c.$$

The theoretical calculations are of necessity somewhat idealized so that, coupled with the tolerance problem, it is hoped that in practice it will be feasible to use harmonics up through the 100th. Power at the 35th harmonic of the S-band rebatron has already been achieved, with work in progress to extend the useable harmonic power to one millimeter wavelength.

To produce power below one millimeter wavelength, an X-band (3 cm) bunching accelerator is being developed. This device will use the rebatron structure followed by a short linear accelerator section to accelerate the bunched beam into the 1 to 3 mev range. The linear accelerator section is necessary since sufficient voltage cannot be developed across a TM_{010} mode cavity at X-band to achieve megavolt beams without voltage breakdown in the structure.

FIGURE 3 X-BAND BUNCHING ACCELERATOR

2.3 Megavolt Coupling Structure Research

The coupling structure work is along two lines: (1) the excitation of the higher order modes of a system to solve the physical size limitation problem, and (2) non-resonant Cerenkov structures.

It is well known that a structure oscillating in a higher order mode can be physically large compared to the resonant wavelength. For example, in the case of the TM_{omn} mode cylindrical cavity shown in Fig. 4 by using large values of the indices m and n , it is seen that D/λ_o and L/λ_o can be made much greater than one.

$$\left(\frac{D}{\lambda_o}\right)^2 = \left(\frac{r_{om}}{\pi}\right)^2 + \left(\frac{nD}{2L}\right)^2 \quad (2)$$

$$\frac{v_p}{c} = \sqrt{1 + \left(\frac{r_{om} 2L}{\pi n D}\right)^2} \quad (3)$$

$$k_+ = \frac{1}{2} \frac{\sin \left[\frac{\pi L}{\lambda_o} \left(\frac{c}{v} - \frac{c}{v_p} \right) \right]}{\left[\frac{\pi L}{\lambda_o} \left(\frac{c}{v} - \frac{c}{v_p} \right) \right]} \quad (4)$$

FIGURE 4 EXCITATION OF TM_{omn} MODES OF CYLINDRICAL METAL CAVITY

Two problems are involved in exciting higher order mode structures: (1) the mode interference problem, and (2) the coupling problem, as seen from Eqs. 3 and 4. The power given up by the beam can be expressed as

$$\mathcal{P} \approx \frac{1}{2} (I_s k_+)^2 R \quad (5)$$

where k_+ is the coupling coefficient given by Eq. 4, and R is the circuit interaction resistance. Unless $v \approx c$, very little power could be extracted from a beam using the TM_{0mn} metal structure shown in Fig. 4.

However, using a beam velocity $v \geq 0.93c$, it has been shown that modes up to the $TM_{02(10)}$ and $TM_{03(10)}$ are practical without using mode suppression techniques. Thus a simple structure, large enough to be fabricated conveniently, can be made to produce radiation below one millimeter.

The current work is directed towards finding a structure whose phase velocity is in the range $0.93c \leq v_p \leq c$ and whose higher order modes can be well separated so as not to cause mode interference. A structure which shows considerable promise in this direction is the dielectric cavity shown in Fig. 5.

FIGURE 5 DIELECTRIC HARMODOTRON

This structure behaves as a high Q cavity only for those modes whose phase velocity is less than the velocity of light c , so that some mode suppression is inherent in the device. Also, since there are two additional parameters b and ϵ associated with this device as compared to the metal structure, additional mode separation can be achieved.

Work is in progress in evaluating the mode properties (a very tedious numerical task) of these structures and the power output that

can be achieved. Initial experiments have checked very well with theory, using a $TM_{01(13)}$ mode at eight millimeters wavelength.

The Cerenkov structure being investigated is a split dielectric cone, as shown in Fig. 6. The cone has been split into two equal sections, the

FIGURE 6 CERENKOV RADIATOR

one section then displaced a distance D relative to the first, to destroy part of the circular symmetry and make the radiator end fire.

The advantage of a megavolt beam is again evident when one examines the E_z field component in the axial hole traversed by the beam.

$$E_z = E_0 \left\{ a_n I_0(Kr) + \frac{\rho_n}{K^2 \epsilon_0} \right\} \epsilon^{in\omega_0(t-z/v)} \quad (6)$$

where

$$K = \frac{2\pi}{\beta\lambda_0} \sqrt{1 - \beta^2}$$

and

$$v = \beta c.$$

As $\beta \rightarrow 1$, $K \rightarrow 0$ and the field becomes more uniform in the r direction, so that the beam does not need to pass close to the dielectric.

2.4 Detectors and Components

The present aim of this work is to develop a set of two and one millimeter components around 0.075×0.034 inch and 0.049×0.022 inch guide, for use in microwave diagnostics of gaseous plasmas.

The signal source for testing components has been the silicon crystal cross guide multiplier, using QK288 and EMI (R9521) eight millimeter klystrons as drivers. Numerous new mechanical and electrical designs are being tried to improve these multipliers to increase their output power. An Amperex DX-151 four millimeter klystron and an Elliott Brothers VX 9206 eight millimeter klystron are being secured for drivers of new multiplying devices.

The machining and mechanical problems of fabricating one millimeter wavelength components have been largely solved. What is needed is better signal sources so that the electrical designs can be improved and better evaluated.

2.5 Present Status of the Work

2.5.1 Rebatron Research

2.5.1.1 S-Band Rebatron

A very important practical technical rebatron problem has been solved this quarter, the problem of feeding a pulsed magnetron into a high Q (greater than 10,000) circuit. The magnetron is ideally suited for a rebatron driving source in that it (1) delivers high pulsed power of the order of a megawatt, (2) is physically very compact in size, and (3) the required pulsed power supply (8 kv at 300 a) can be packaged in a small unit with no difficult voltage or components problems. Its only drawback has been that it will not fire directly into a high Q circuit. In the past, a series Tee stabilizing circuit has been used, which results in more than half of the magnetron power being dissipated in a stabilizing resistor or load. To make up for this loss, a second magnetron has been added to the circuit, thereby doubling the equipment requirements.

This quarter a high power ferrite isolator has been secured from Cascade Research which, when incorporated into the appropriate microwave circuit, permitted practically the entire magnetron power to be fed directly into our high Q accelerating cavity. This achievement will permit us to package our rebatrons in a portable system with size on the order of

a half relay rack. More important, this more efficient use of magnetron power should permit us to build a K-band rebatron-accelerator system, where high power is at a premium, in the near future.

2.5.1.2 X-Band Rebatron

The PACE analogue computer has been programmed, and curves of particle displacement and velocity have been computed for field strengths from 50 to 500 kv/cm for injection velocities ranging from 0.24 c to 0.40 c. These calculations will permit us to design the rebatron section of our 3 cm bunching accelerator. The linear accelerator section, shown in Figure 3, has not as yet been programmed. It is planned to carry out this computation while the rebatron section is under construction, since the two sections can be designed somewhat independently.

2.5.2 Beam Coupling Schemes

Work on coupling schemes this quarter was limited entirely to the dielectric harmodotron. The problems involved with the excitation of any higher order mode device are (1) evaluation of the mode properties of the structure, (2) calculation of the power output, (3) design of the structure to obtain the maximum output power with the minimum of mode interference, and (4) experimental verification.

This quarter the calculation of the TE modes of teflon cavities has been completed so that a good comparison of the TM and TE modes of metal and dielectric cavities can now be made.

Preparations have been made to perform the next dielectric harmodotron experiment at 5.18 millimeters where the components can be thoroughly bench tested.

2.5.3 Detecting and Measuring Techniques

Crystal multipliers involve (1) the synthesis of a non-linear frequency multiplying circuit, and (2) a difficult mechanical fabrication problem. Up until this quarter, our effort on these multipliers has been predominately concerned with mechanical designs. We have been trying cross-guide, straight guide, tapered guide, and built-in guide crystal, or coax cartridge crystal, and other arrangements in an effort to simplify some of the mechanical problems. While all of the fabrication problems are not solved, we can now build almost anything we can design. The next step is to take a more critical look at the electrical design problems.

Some time was spent this quarter on examining some analog circuits in order to attack the frequency conversion efficiency problem. The first circuit tried gave a second harmonic power about 13 db below the fundamental, a value comparable to the best crystal circuits now being used.

Work was initiated this quarter on a 16 microinch bolometer detector for our 0.049×0.022 inch waveguide. Designing a mount whereby the Wollaston wire can be etched directly in the mount is a bit of a problem. Several ideas were tried without success. However, it is believed that the detector can be made with further improvements in techniques.

A 1N53 coax crystal is physically too large to be placed across a 0.049×0.022 inch guide. What is needed is a crystal cartridge roughly one third the size of a 1N53. Several scaled down crystal cartridges were constructed to examine the fabrication problems involved. At five millimeters, these crystals in an appropriate mount, had a sensitivity roughly one-fourth that of a 1N53. However, by better crystal surface treatment, it is believed that the sensitivities can be made equal.

2.6 Personnel

The present staff assigned to Contract AT(11-1)-392 includes:

<u>Supervision</u>	<u>Percent Time</u>	<u>Date Assigned to contract</u>
Paul D. Coleman, Professor Director	66 2/3	1 April 1956
<u>Staff</u>		
Andrew Swago, Instructor	50	1 April 1956
<u>Research Associates and Assistants</u>		
Harold Spuhler, Research Assistant	75	1 September 1956
Richard Kenyon, Research Assistant	75	1 April 1956
Richard Becker, Research Assistant	100	1 December 1956
Joseph Stafford, Research Assistant	50	1 February 1957
<u>Electronic Technicians</u>		
Kenneth Bartlett, Sr. Elec. Tech.	80	1 April 1956
Allen B. Wilson, Sr. Elec. Tech.	33	1 April 1956
Garry Paddick, Student (Hourly)	(15 Hrs. week)	1 June 1956
<u>Shop Technicians</u>		
John F. Lowe, Instrument Maker	100	1 April 1956
Lewis Claybaugh, Senior Laboratory Mechanic	75	1 March 1957

Clerks

Donald Pritchard	25	1 April 1956
Richard Ripper	25	1 April 1956

2.7 Papers, Reports, Publications, Visits

2.7.1 Quarterly Reports

<u>Title</u>	<u>Report Period</u>
Quarterly Report No. 1	1 March to 1 June 1956
Quarterly Report No. 2	1 June to 1 September 1956
Quarterly Report No. 3	1 September to 1 December 1956
Quarterly Report No. 4	1 December to 1 March 1957
Quarterly Report No. 5	1 March to 1 June 1957
Quarterly Report No. 6	1 June to 1 September 1957

2.7.2 Technical Reports

"The Harmodotron--A Beam Harmonic Higher Order Mode Device for Producing Millimeter and Submillimeter Waves," M.D. Sirkis, Technical Report No. 1, 10 September 1956.

2.7.3 Conference Papers

"Megavolt Electronics and the Submillimeter Wave Problem," presented by P.D. Coleman at the Fourteenth Annual Conference on Electron Tube Research, June 1956, Boulder, Colorado.

"Megavolt Electronics Millimeter Wave Coupling Structure Research at the University of Illinois," presented by P.D. Coleman at the Tri-Service Millimeter Wave Symposium in September 1957 at Fort Monmouth, N.J.

2.7.4 Papers Accepted for Publication

The following papers were published in the September 1957 issue of the Journal of Applied Physics

1. "The Theory of the Rebatron--a Relativistic Electron Bunching Accelerator for Use in Megavolt Electronics," P.D. Coleman.
2. "The Design and Evaluation of a 3 kmc Rebatron," I. Kaufman and P.D. Coleman (this paper was jointly supported by Contracts AT(11-1)-392 and AF18(603)-62.
3. "The Harmodotron--A Megavolt Electronics Millimeter and Submillimeter Wave Generator," M.D. Sirkis and P.D. Coleman.

The following paper has been accepted for publication in the IRE Trans., PGED:

"Dielectric Slow-Wave Structures for the Generation of Power at Millimeter and Submillimeter Wavelengths," R.H. Pantell, P.D. Coleman, R.C. Becker.

2.7.5 Visits and Conferences

P. Coleman visited Dr. Mark Heald at Princeton and Mr. Donald Slager at Los Alamos during the month of September to discuss millimeter waves and plasma diagnostics.

Dr. Mark Heald visited the Ultramicrowave Group in October to see our work first hand and to discuss plans for mutual assistance.

P. Coleman and Dr. Charles Wharton of Livermore had occasion to discuss recent progress during the NEC meeting in Chicago in October.

P. Coleman visited Dr. A.E. Ruark and Dr. H. Roderick in Washington, D.C. in September to review the past work on the contract and to discuss future plans.

3. DETAILED FACTUAL DATA

3.1 Rebatron

3.1.1 Purpose

The objective of this phase of the program is the design and development of a practical, compact, portable rebatron. There are four subphases to this work.

1. Microwave circuit problem
2. Electron injection problem
3. Electron trajectory calculations
4. Electronic instrumentation problem.

3.1.2 Electron Injection Problem - R. Kenyon

3.1.2.1 Purpose

The aim of this work is to investigate the electron dynamics problem in the rebatron from the point of view of increasing the accelerated current to its largest practical value.

3.1.2.2 Present Status of the Accelerating Cavity

Because the use of the E-plane bend made it impossible to change the size of the coupling hole once the cavity was brazed together, a test cavity was built without the bend for this purpose. For a single port cavity, the correct coupling hole size will give a 1 to 1 VSWR (strictly speaking, it is necessary to have a small amount of power reflected to the magnetron to lock the magnetron on the cavity frequency). By using the side-band technique with a frequency stabilized oscillator, the coupling hole diameter was determined to be 23/32 inch for a SWR of less than 1 db. This was for the test cavity without the E-plane bend. This coupling hole size was then used for the cavity to be used in the rebatron and was brazed together, including the E-plane bend.

The cavity was then checked experimentally to determine whether the 23/32 inch coupling hole diameter was indeed the correct size. First, the resonant frequency was determined to be 2843.5 mc/s by using a 60 cps modulated klystron, a magic-tee and a co-axial wave meter. The frequency stabilized oscillator was then set to 2844.1 mc/s and the lower side-band was used to measure the curves shown in Fig. 7. The setup also included the demountable vacuum seal, which is necessary in the rebatron, so that the curves in Fig. 7 include the effect of the coupling hole, the E-plane bend, and the vacuum seal on the match. From Fig. 7, the following quantities are known: SWR on resonance is less than 1 db and is overcoupled; the position of the minimum on resonance is 3.40 cm on the generator side of the

FIGURE 7 SWR AND POSITION OF MINIMUM VS. SIDE-BAND FREQUENCY

vacuum seal flange; $Q_L \approx 12,000$.

It may be noticed that the resonant frequency of this cavity is about 60 mc/s higher than the previous cavities that have been constructed. This is due, as shown in Fig. 8, to the concave entrance end wall.

This completes the low-power measurements on the cavity and it is now ready for testing with the high-power microwave circuit.

3.1.2.3. Present Status of the Microwave Circuit

With the receipt of a high power ferrite isolator on loan from Cascade Research Corporation, the microwave circuit problem has taken on a new aspect. At present, tests are being carried on to determine whether this isolator can be used to replace the stabilizing-load-H-plane-tee combination. The present status of these tests will be discussed in Section 3.1.4.

3.1.2.4 Present Status of the Injection Tube

Two high voltage vacuum bushings were received during this quarter for testing. Figure 9 shows one of the terminals brazed into a copper base plate for use in an injection tube. It has a number of physical advantages over the present gun which utilizes a metal-to-glass seal at the base plate and a porous ceramic disc for mounting the electrodes. First, the metal-to-glass seal is eliminated since the bushing is vacuum tight; second, it can be high temperature brazed which provides a clean, leak-free joint; third, it is a glazed ceramic, which makes it possible to keep it clean.

A test was performed with this bushing by placing it inside one of the present injection tube barrels, evacuating it, and applying pulse voltage to the mounting posts. Corona was noticed at the mounting posts at about 29 kv and arcing at the rear of the tube (in air) started at about 30 kv. The bushing, therefore, is not much better, from a breakdown standpoint, than the present design, since the latter has been used up to 27 kv. Its only advantages are the physical ones previously mentioned. An attempt will be made to obtain a bushing suitable to 40 kv.

3.1.2.5 Present Status of Portable Vacuum Station

Except for a few minor items, the control panels for the front of the table are finished. Provisions for supplying water and power to the table have also been completed and the internal power wiring has been completed. The rest of the work necessary to complete the table, such as the internal

FIGURE 3 SINGLE PORT ACCELERATING CAVITY DIMENSIONS

FIGURE 9 HIGH VOLTAGE BUSHING

FIGURE 10 ANALOG COMPUTER INSTALLATION

water supply, placement of the vacuum system, placement of the pulse transformers, etc., is contingent upon the location of the accelerating cavity, which is in turn contingent upon the method of magnetron stabilization to be used (See Section 3.1.4).

3.1.3 Rebatron Design above 3 kmc/s - H. Spuhler

3.1.3.1 Purpose

The purpose of this phase of the project is two-fold:

1. To investigate the problems involved in operation of a rebatron at frequencies above 3 kmc/s and to determine the highest frequency useable, considering components presently available.
2. To construct and test a rebatron operating at the highest frequency above 3 kmc/s for which design factors are practical.

3.1.3.2 Present Status

Particle displacement and relative velocity curves have been obtained using the PACE Analog Computer. The range in peak axial electric field covered from 50 to 500 kv/cm. The range in injection relative velocity covered from 0.24 to 0.40. The program was checked using results for the 10 cm rebatron obtained using the ILLIAC Digital Computer. Estimated accuracy for the test problem was 0.5% in the region of interest about π radians for the cavity phase.

Figures 10 and 11 show the analog computer installation and a closeup of the data curves as obtained from the Variplotter. The two curves shown represent electron displacement along the cavity axis and electron relative velocity, both drawn using cavity phase angle for the abscissa variable. Since the proportionality constant $H = \frac{e E_0}{\omega m_0 c}$ depends in ratio of E_0 to ω , the families of curves obtained for various values of H provide a universal set for electron trajectories through cavities operating in the TM_{010} mode. Thus the data obtained will be used in the consideration of the K-band rebatron as well as for the X-band design.

The form in which the data are presented provides a relatively simple determination of proper cavity dimensions in contrast to the Illiac data. The digital program involves integration to a fixed cavity length, which must be chosen as one of the preset parameters. In both cases the families of ideal injection velocity distribution curves, etc., must be manually plotted.

FIGURE 11 CLOSE-UP OF DATA CURVES OBTAINED FROM THE VARIPLOTTER

Work is now in progress on plotting ideal injection velocity distributions for the various conditions so that bunch and momentum distributions may be optimized. From results to date it seems that, for an operating frequency of 9.3 kmc/s, a cavity length of 1.08 cm with input power of 0.1 megawatt will be close to optimum. For this condition, peak axial field will be 498 kv/cm, a value which should not exceed breakdown criteria for the cavity when properly finished and evacuated.

With the average output relative velocity assumed to be 0.8, a rough calculation indicates that space bunching to within 0.1 mm will be obtained if the ideal injection velocity distribution can be matched so that the output phase variation is less than 0.025 radian or about 1.45 degrees. While results for the modulating cavity have not been plotted as yet, experience with the 10 cm rebatron indicates this is practical. Velocity variation within the bunch should be very small since the ejection velocity changes are small in this region. No momentum calculations have been made to date.

Work on programming for the tapered section of the linear accelerator has been deferred until the rebatron design has been completed so that construction of the 3 cm rebatron may be under way while the accelerator calculations are in progress.

Because of the very successful results obtained in using a ferrite isolator for magnetron stabilization, such a system will be used rather than one using a waveguide tee or gas-tube switch. The mechanical design aspects of the isolator system are much simpler and experimental results (reported in Section 3.1.4) indicate that this is the most efficient way to couple a magnetron to a high-Q cavity in a pulsed system. Work on the gas-tube switch and waveguide tee methods of stabilization has been discontinued.

The last phase of the rebatron design is that of the Pierce gun beam injection system. Present plans are to use the present gun design modified to place the minimum spot at the center of the accelerating cavity. Work on this phase will begin after designs have been completed for the modulating and accelerating cavities.

3.1.4 Magnetron Stabilization - H. Spuhler, R. Kenyon

One of the several problems involved in rebatron design has been the stabilization of the magnetron oscillator used to drive the high-Q accelerating cavity. In the past, stabilization was accomplished by coupling to the cavity through a waveguide tee with its side arm terminated by a matched load. The tees used with the first two machines were designed for a 1:1 power division. Since that time tees having various power ratios have been tested. The highest ratio used was 4:1, that is, 80% of the available power reached the cavity. For this case, however, stabilization was not satisfactory. Since at least 0.8 megawatt at the cavity is required to produce the desired output energy level at 10 cm, a one-magnetron system would require either a more efficient coupling system or a tube having higher available power output.

As indicated in the last report a gas-tube switch was tried. The waveguide tee system was modified by introducing a slotted section between the tee and the matched load. Through the slot an evacuated glass tube was placed with its axis parallel to the electric field. The slot, together with adjustment of the gas pressure in the tube permitted firing of the tube at various intensity levels and at various positions with respect to the reference plane of the tee. Expectations were that a proper choice of operating conditions would permit the tube to fire into the matched load until oscillations had started to build up in the cavity, at which time firing of the gas tube would switch out the load and couple the magnetron directly to the cavity. Initial attempts to secure stabilization in this way were unsuccessful. Operation was intermittent and magnetron moding was excessive. Results indicated the slot should be eliminated and a sealed tube used, together with a shorter line length to the load. Further work in this direction was suspended on receipt of a 10 cm high-power ferrite isolator loaned to the project for experimental use.

With the isolator connected directly to the magnetron output, the cavity was coupled to the isolator through a directional coupler and a phase-shifter which would permit precise adjustment of electrical line length. Rough adjustment of line length was obtained using a short matching section containing a window to permit evacuation of the cavity without sealing the entire guide. Power fed toward the cavity, power delivered to the cavity, and power reflected from the cavity were monitored, using an oscilloscope

to view the pulse envelope. Figures 12 and 13 show the system both with and without the lead shielding in place around the cavity. Since comparison with the performance of the waveguide tee method was to be made, the magnetron operating conditions were kept constant, except for slight tuning adjustments. X-ray yield from the cavity was measured with the radiation monitor placed along the cavity axis at a distance of three inches from the end wall.

To obtain a qualitative performance rating the test was run without means of precise power measurement. In each case, magnetron operating conditions were fixed and the detector tuning and oscilloscope gain unchanged. A small change in phasing was required when the tee system was used in place of the isolator. Pictures of the monitor waveforms and comparative x-ray yield were used to judge relative performance.

The maximum x-ray yield using the isolator was 1.5 r/hour while that obtained using the tee system was only 0.1 r/hour. Figure 14a shows the reflected power pulse for the isolator system below that of the cavity power monitor. The top pair show the cavity power rising exponentially to an essentially flat top, as is necessary for proper operation of the rebatron. The reflected power decays very nearly to the base line, indicating that more than 90% of the power is being delivered to the cavity. The bottom pair shows the reflected power waveform inverted for comparison of the rise and decay times of the pulses.

Figure 14b shows the same waveforms as taken using the waveguide tee for stabilization. The increase in reflected power from the cavity, hence the decrease in power delivered to the cavity, is evident from the shape of the pulse. Also, as previously stated, the x-ray yield decreased from 1.5r/hour to 0.1r/hour. No quantitative data were taken from which to determine the magnitude of the power delivered to the cavity. However, it seems evident that the isolator system is significantly superior in terms of performance as well as mechanical simplicity and convenience.

For this reason quantitative measurements will be made of cavity power using the 10 degree spectroscope which was constructed for momentum measurements on the other two machines. Momentum measurements will provide a means of determining the field in the cavity, hence the power actually delivered to the cavity. One of the new Pierce guns will be used to provide the beam injected along the cavity axis. The gun and spectroscope assemblies have been installed and aging of the cathode is now in process.

FIGURE 12 INSTRUMENTATION FOR ISOLATOR TEST

FIGURE 13. MICROWAVE CIRCUIT FOR ISOLATOR TEST

FIGURE 14A MONITOR WAVEFORMS FOR
ISOLATOR STABILIZATION

FIGURE 14B MONITOR WAVEFORMS FOR
THE TEE STABILIZATION

3.2 Beam Coupling Schemes

3.2.1 Purpose

This part of the research work has as its goal the origination of generation schemes using the million volt, bunched electron beam from the rebatron to produce high pulsed power in the 0.1 to 1 mm wavelength region of the electromagnetic spectrum. The general methods of approach to the problem are along two lines:

- 1) Extending existing tube techniques by means of megavolt electronics.
- 2) Using the Doppler and Cerenkov effects in direct radiation devices.

3.2.2 The Slow-Wave Dielectric Harmodotron - R.C. Becker

3.2.2.1 Introduction

During the past interval, analysis of the slow-wave, dielectric, higher order mode resonator has included the computation of the TE mode design curves, plots of the mode patterns, and the preparation of a five millimeter experiment using the rebatron. Detailed theoretical investigation of the general behaviour of this resonant structure is being pursued because its properties are distinct from those of the more conventional cavity resonators, and since its mode separation properties may provide a device which is extremely advantageous in various microwave applications employing resonant cavities. The slow-wave properties of this device make its utilization in beam coupling problems particularly attractive, due to the increased coupling efficiency and greater power output ordinarily attainable. Experimentation continues in an effort to learn more about the actual performance of this structure, and as verification of the theory used to describe its behaviour.

3.2.2.2 Article for Publication

The paper entitled, "Dielectric Slow-Wave Structures for the Generation of Power at Millimeter and Submillimeter Wavelengths," by Richard H. Pantell, Paul D. Coleman, and Richard C. Becker, has been accepted for publication. The article is to appear in the April, 1958, issue of the Transactions on Electron Devices published by the Institute of Radio Engineers, New York.

3.2.2.3 Analysis of the Slow-Wave Dielectric Harmodotron

3.2.2.3.1 Introduction

Theoretical investigation of this device (Fig. 15) during past months has already provided information which was of particular use in applications of the slow-wave dielectric resonator as a beam coupling structure. This has been due to the fact that the primary aim of this investigation is to generate millimeter and submillimeter waves by means of the megavolt electronics technique which directly involves a high energy, tightly bunched electron beam. In such applications the beam passes through the structure along the axis of symmetry and is assumed to be a symmetrical source giving rise to fields which are symmetrical about the axis of symmetry (no ϕ -variation). Thus, only the TM_{omn} modes are of interest in describing the energy exchange between the beam and the resonator under such conditions. Design curves and mode charts, together with power calculations for operation of this device in TM_{omn} modes, have already appeared in previous reports published under this contract.

The true advantage of the slow-wave dielectric resonator as a device which can be designed for negligible mode interference cannot be determined, however, until the investigation of all possible modes which can exist within the structure has been completed. Complementing the TM_{omn} mode information appearing in Technical Progress Report No. 6 (15 September 1957), there appear in this report the TE_{omn} mode charts for this device. These two sets of modes completely describe the field behaviour of this resonant structure when the fields are axially symmetric, that is, when no ϕ -variation exists. Design curves for the TE_{omn} modes are also included, since other microwave applications may require resonance in a TE mode.

Representative field plots describing the behaviour of the fields at the end walls are also presented. Since the output waveguide coupling aperture is located in an end wall, this information permits placement of the output waveguide at the most desirable location. Continuity of these field plots at the boundaries of the dielectric cylinder ($\rho = a, b$) has also served as a check on the validity of certain of the previous power calculations.

FIGURE 15 SLOW-WAVE DIELECTRIC HARMODOTRON

3.2.2.3.2 The TE_{omn} Mode Fields

The procedure for deriving the characteristic equation for the TE_{omn} modes, and obtaining there-from the design curves and the mode charts, is similar to that used in the analysis of the TM_{omn} modes. Because the method involves much detail and is quite lengthy, and since the complete analysis for the TM_{omn} modes already appears in Technical Progress Reports No. 4 (15 March 1957), No. 5 (15 June 1957), and No. 6 (15 September 1957), only a synopsis of the analytical technique will be presented.

Solutions to the wave equations derived from Maxwell's equations are found for the structure pictured in Fig. 15. The general solution is of the form, assuming $e^{j\omega t}$ time dependence,

$$H_{zs}(\rho, \phi, z, b) = \left[A_s' J_{v_s}(K_s \rho) + B_s' N_{v_s}(K_s \rho) \right] \left[C_s' e^{jv_s \phi} + D_s' e^{-jv_s \phi} \right] \left[E_s' e^{\gamma_s z} + F_s' e^{-\gamma_s z} \right] e^{j\omega t}$$

where

$$\gamma_s = \alpha_s + j \beta_s \quad - \text{propagation constant along the } z \text{ direction}$$

$$K_s = \sqrt{(\gamma_s^2 + \omega^2 \mu_s \epsilon_s) - j\omega \mu_s \sigma_s}$$

v_s - constant arising from the solution of the scalar wave equation by means of the method of separation of variables.

$J_{v_s}(K_s \rho)$, $N_{v_s}(K_s \rho)$ - Bessel functions of the first and second kinds, respectively.

s - an index number identifying a given medium in problems involving several media.

The media within the slow-wave dielectric resonator are assumed to be homogeneous, isotropic, lossless, and charge-free so that, upon assuming the fields to be axially symmetric ($v_s = 0$), application of the boundary conditions at the end walls then simplifies the general solution to the form:

$$H_{zs} = \left[A_s' J_0(K_s \rho) + B_s' N_0(K_s \rho) \right] \sin \beta_s z e^{j\omega t}$$

with

$$\beta = \frac{n\pi}{L}, n = 0, 1, 2, \dots$$

By definition, $E_z = 0$ for the TE modes so that the only field components under these conditions are H_z , H_ρ , and E_ϕ .

The slow-wave property of this device requires that the phase velocity of the waves moving in the z-direction be equal to the electron velocity of the beam to which it is ordinarily coupled. Since the phase velocity along the z-direction, v_p , must equal the electron velocity, v_e , and this latter velocity is always less than the velocity of electromagnetic propagation, c , in the medium in which the beam exists, then the arguments of the Bessel functions in regions I and III will be imaginary numbers. The modified Bessel functions $I_0(\gamma\rho)$ and $K_0(\gamma\rho)$, respectively, are therefore used to describe the fields in these regions. The values for the arguments in the respective regions follow from:

$$K_s = \sqrt{\omega^2 \mu_s \epsilon_s - \beta_s^2} = \frac{\omega}{c_s} \sqrt{1 - \left(\frac{c_s}{v_{ps}}\right)^2}$$

In region I, the region of the beam, $v_p = v_c < c_o$, but $v_{ps} = \frac{\omega}{\beta_s}$ will be the same in all three regions since $\beta_1 = \beta_2 = \beta_3$ follows from the boundary conditions. Therefore,

$$K_1 = K_3 = j \gamma$$

$$\gamma = \frac{\omega}{c_o} \sqrt{\left(\frac{c_o}{v_p}\right)^2 - 1} = \frac{2\pi}{\lambda_o} \sqrt{\left(\frac{c_o}{v_p}\right)^2 - 1}$$

and

$$K_2 = \Gamma = \frac{\omega}{c_o} \sqrt{\frac{\epsilon}{\epsilon_o} - \left(\frac{c_o}{v_p}\right)^2} = \frac{2\pi}{\lambda_o} \sqrt{\frac{\epsilon}{\epsilon_o} - \left(\frac{c_o}{v_p}\right)^2}.$$

For teflon as the dielectric material of the cylinder, $\frac{\epsilon}{\epsilon_o} = 2.08$ and the permissible range of values for the phase velocity, which will cause resonance under the desired conditions, is then

$$0.693 \leq \frac{v_p}{c_o} \leq 1.0.$$

The field expressions from which the total TE_{omn} fields for the slow-wave,

dielectric resonator are derivable, are, then:

$$H_{z1} = A' I_0(\gamma\rho) \sin \beta z e^{j\omega t}$$

$$H_{z2} = [B' J_0(\Gamma\rho) + C' N_0(\Gamma\rho)] \sin \beta z e^{j\omega t}$$

$$H_{z3} = D' K_0(\gamma\rho) \sin \beta z e^{j\omega t}$$

$$E_{z1} = E_{z2} = E_{z3} = 0.$$

3.2.2.3.3 Design Curves for the TE_{omn} Modes

Having obtained the field expressions for the TE_{omn} modes of the slow-wave dielectric resonator, one then derives the characteristic equation from the boundary conditions at the inner radius, $\rho = a$, and the outer radius, $\rho = b$, of the dielectric cylinder. The characteristic equation for the TE_{omn} modes is found to be:

$$\frac{\frac{p}{q} J_1(q) - \frac{I_1(p)}{I_0(p)} J_0(q)}{\frac{p}{q} N_1(q) - \frac{I_1(p)}{I_0(p)} N_0(q)} = \frac{\frac{w}{v} J_1(v) + \frac{K_1(w)}{K_0(w)} J_0(v)}{\frac{w}{v} N_1(v) + \frac{K_1(w)}{K_0(w)} N_0(v)}$$

where,

$$p = \frac{a}{\lambda_0} 2\pi \sqrt{\left(\frac{c_0}{v_p}\right)^2 - 1} = \frac{a}{b} w$$

$$q = \frac{a}{\lambda_0} 2\pi \sqrt{\frac{\epsilon}{\epsilon_0} - \left(\frac{c_0}{v_p}\right)^2} = \frac{a}{b} v$$

When parametric values are affixed to ϵ/ϵ_0 and v_p/c_0 , the left side of the characteristic equation becomes a function of a/λ_0 alone, $f(a/\lambda_0)$, and the right side a function of b/λ_0 only, $g(b/\lambda_0)$. Technical Progress Report No. 5 (15 June 1957) describes the manner in which these functions are computed and graphed, and how the design curves are then obtained. The design curves, a/λ_0 versus b/λ_0 , for the TE_{omn} modes of the slow-wave,

dielectric resonator appear in Figs. 16, 17, 18, 19, 20, and 21. These curves present the values of the radii a and b which are compatible for resonance in a desired mode, at any frequency.

3.2.2.3.4 The TE_{omn} Mode Charts

The mode charts consist of graphs of b/λ_0 versus b/L . Values for b/λ_0 are necessarily taken from the design curves, and $b/L = (b/\lambda_0) \left(\frac{2 c_0}{n v_p} \right)$ since $L = \frac{n}{2} \frac{v_p}{c_0} \lambda_0$. Identical to the case for the TM_{omn} modes, the parametric values for which modes are plotted are:

$$\epsilon/\epsilon_0 = 2.08$$

$$v_p/c_0 = 0.80, 0.88, 0.93, 0.97, 1.00$$

$$m = 1, 2, 3$$

$$n = 1, 2, 3, 4, 5, 10, 15$$

$$a/b = 0.2, 0.5, 0.8.$$

Plotted to a common scale, the TE_{omn} mode charts are presented in Figs. 22, 23, and 24. The ratio a/b is observed to have a profound effect on the mode separation capability of this device, and it is the existence of this parameter in the slow-wave dielectric resonator which distinguishes it from the conventional cylindrical cavities.

3.2.2.3.5 Complete Mode Representation for the Case of Axially Symmetric Fields in the Slow-Wave Dielectric Resonator

For the special case of only axially symmetrical fields, $v_s = 0$ in the slow-wave dielectric resonator, the hybrid modes not being supported by the structure under this condition. Therefore, the complete mode charts for the slow-wave dielectric cavity will consist of the superposition of the individual TE_{omn} and TM_{omn} charts. Figure 25 is then the complete mode description for the teflon dielectric resonator where $a/b = 0.5$, and Fig. 26 is the complete mode description for $a/b = 0.2$. The mode-separating capability of this device is again apparent when these two graphs are compared.

The improvement in mode separation performance which is afforded by the slow-wave dielectric resonator over cylindrical metal cavities is illustrated by comparing the TM_{omn} modes of Fig. 26 with those for the metal cavity in Fig. 27. Both plots of the TM_{omn} modes are presented on

FIGURE 16 THE CAVITY DIMENSIONS b/λ_0 VERSUS a/λ_0 FOR THE TE_{am_n} MODES OF THE DIELECTRIC HARMODOTRON, WHERE $\epsilon/\epsilon_0 = 2.08$ AND $v_p/c = 0.70$. (λ_0 = FREE SPACE WAVELENGTH).

FIGURE 17 THE CAVITY DIMENSIONS b/λ_0 VERSUS a/λ_0 FOR THE TE_{omn} MODES OF THE DIELECTRIC HARMODOTRON, WHERE $\epsilon/\epsilon_0 = 2.08$ AND $v_p/c = 0.80$. (λ_0 = FREE SPACE WAVELENGTH).

FIGURE 18 THE CAVITY DIMENSIONS b/λ_0 VERSUS a/λ_0 FOR THE TE_{0mn} MODES OF THE DIELECTRIC HARMODOTRON, WHERE $\epsilon/\epsilon_0 = 2.08$ AND $v_p/c = 0.88$. (λ_0 = FREE SPACE WAVELENGTH).

FIGURE 19 THE CAVITY DIMENSIONS b/λ_0 VERSUS a/λ_0 FOR THE TE_{0mn} MODES OF THE DIELECTRIC HARMODOTRON, WHERE $\epsilon/\epsilon_0 = 2.08$ AND $v_p/c = 0.93$. (λ_0 = FREE SPACE WAVELENGTH).

FIGURE 20 THE CAVITY DIMENSIONS b/λ_0 VERSUS a/λ_0 FOR TE_{omn} MODES OF THE DIELECTRIC HARMODOTRON, WHERE $\epsilon/\epsilon_0 = 2.08$ AND $v_p/c = 0.97$. (λ_0 = FREE SPACE WAVELENGTH).

FIGURE 21 THE CAVITY DIMENSIONS b/λ_0 VERSUS a/λ_0 FOR THE TE_{omn} MODES OF THE DIELECTRIC HARMODOTRON, WHERE $\epsilon/\epsilon_0 = 2.08$ AND $v_p/c = 1.00$. (λ_0 = FREE SPACE WAVELENGTH).

FIGURE 22 TE_{omn} MODES FOR $a/b = 0.2$

FIGURE 23 TE_{omn} MODES FOR $a/b = 0.5$

FIGURE 24 TE_{omn} MODES FOR $a/b = 0.8$

FIGURE 25 THE TM_{0mn} AND TE_{0mn} MODES FOR THE SLOW-WAVE DIELECTRIC RESONATOR, WITH $a/b = 0.5$

FIGURE 26 THE TM_{0mn} AND TE_{0mn} MODES FOR THE SLOW-WAVE DIELECTRIC RESONATOR, WITH $a/b = 0.8$

FIGURE 27 TM_{omn} MODE CHARTS FOR CYLINDRICAL METAL CAVITIES, TOGETHER WITH AN INDICATION OF THE RELATIVE LOCATION OF THE TE_{omn} MODES.

the same scale for purposes of direct comparison. Figure 27 also includes an indication of the intercepts for the various families of TE_{omn} modes, and thereby serves to indicate the highly complex and crowded mode pattern for the axially symmetric fields of the conventional cavities. The mode separation property of the slow-wave structure, on the other hand, can be enhanced even more as the ratio a/b is increased even further. The limiting value for this ratio is obviously one.

3.2.2,3.6 Field Plots for the TM_{omn} Modes

Output power from the slow-wave dielectric resonator is presently obtained by coupling an output waveguide to the resonator fields through an aperture in an end wall. It is therefore desirable to determine whether or not an optimum location for the output aperture exists, and, if so, how this position is determined.

The answer to these questions lies in the investigation of the resonator fields at the end walls. For the TM_{omn} modes, the expressions for the fields at the end walls become:

$$E_{\rho 1} = E_{\rho 2} = E_{\rho 3} = 0$$

$$E_{z1} = A I_0(\gamma\rho) \cos \omega t$$

$$E_{z2} = [B J_0(\Gamma\rho) + C N_0(\Gamma\rho)] \cos \omega t$$

$$E_{z3} = D K_0(\gamma\rho) \cos \omega t$$

$$H_{\phi 1} = -A \frac{\omega \epsilon_0}{\gamma} I_1(\gamma\rho) \sin \omega t$$

$$H_{\phi 2} = \frac{-\omega \epsilon}{\Gamma} [B J_1(\Gamma\rho) + C N_1(\Gamma\rho)] \sin \omega t$$

$$H_{\phi 3} = \frac{\omega \epsilon_0}{\gamma} D K_1(\gamma\rho) \sin \omega t.$$

From the boundary conditions at $\rho = a$ and $\rho = b$, the constants B , C , and D can be normalized with respect to A . The field expressions are then explicitly determined except for the arbitrary amplitude factor A which appears in each of the formulas.

The time independent amplitude distributions for the electric field are plotted in Figs. 28, 29, and 30, where the inner cylinder radius has been fixed at $a/\lambda_0 = 0.4$ and $v_p/c_0 = 0.93$. The outer radius is then permitted to take on values corresponding to the mode numbers $m = 1, 2, 3$,

FIGURE 28 THEORETICAL, TIME INDEPENDENT, RELATIVE FIELD INTENSITY E_z FOR THE TM_{01n} MODES WITH $v_p/c_0 = 0.93$, $a/\lambda_0 = 0.4$, and $z = 0, L$.

FIGURE 29 THEORETICAL, TIME INDEPENDENT, RELATIVE FIELD INTENSITY E_z FOR THE TM_{02n} MODES WITH $v_p/c_0 = 0.93$, $a/\lambda_0 = 0.4$, and $z = 0, L$

FIGURE 30 THEORETICAL, TIME INDEPENDENT, RELATIVE FIELD INTENSITY E_z FOR THE TM_{03n} MODES
 WITH $v_p/c_0 = 0.93$, $a/\lambda_0 = 0.4$, and $z = 0, L$

as found in the design curves for the TM_{0mn} modes. Similar plots for the magnetic field at the end walls appear in Figs. 31, 32, and 33. These graphs clearly indicate the existence of an optimum location for coupling to an output waveguide, and the necessity for proper positioning of the output aperture if maximum power output is to be achieved. From these field plots one can then locate the output aperture at the most desirable position, depending upon whether the output couples to the electric or the magnetic field of the slow-wave dielectric resonator.

3.2.2.4 Millimeter Experiment

During the past interval, preparations have been made for performing a beam coupling experiment with the slow-wave dielectric harmodotron at a wavelength of 5.18 millimeters. This wavelength corresponds to the twenty-first harmonic of the rebatron frequency used to modulate the beam.

This particular frequency was chosen for two reasons. First, this is the highest frequency presently available from QK295 bench-type signal sources at this laboratory. By means of bench measurements, the microwave properties of the resonator can be determined and optimized with relative ease before being used with the rebatron under vacuum.

Second, the last successful experiment utilizing the slow-wave dielectric harmodotron for coupling to the relativistic electron beam of the rebatron was performed at a wavelength of nine millimeters. It is felt that this step in frequency will be significant in establishing the usefulness of this device at higher and higher frequencies.

The preliminary bench measurements have already been completed, and the rebatron experiment is scheduled to take place in about two weeks.

3.2.2.5 Plans for the Next Interval

Experimental investigation of the slow-wave dielectric resonator will continue, in connection with the experiment described in the preceding section. The analysis of this structure will next involve the investigation of the boundary value problem approached from the most general considerations. This will involve the study of the hybrid modes for this device.

FIGURE 31 THEORETICAL, TIME INDEPENDENT, RELATIVE FIELD INTENSITY H_ϕ FOR THE TM_{01n} MODES WITH $v_p/c_0 = 0.93$, $a/\lambda_0 = 0.4$, AND $z = 0, L$

FIGURE 32 THEORETICAL, TIME INDEPENDENT, RELATIVE FIELD INTENSITY H_ϕ FOR THE TM_{02n} MODES WITH $v_p/c_0 = 0.93$, $a/\lambda_0 = 0.4$, and $z = 0, L$.

FIGURE 33 THEORETICAL, TIME INDEPENDENT, RELATIVE FIELD INTENSITY H_ϕ FOR THE TM_{03n} MODES. WITH $v_p/c_0 = 0.93$, $a/\lambda_0 = 0.4$, and $z = 0, L$.

3.3 Detecting and Measuring Techniques

3.3.1 Purpose

The objective of this research is to develop suitable detectors and power and frequency measuring instruments for evaluating the characteristics of the radiation produced by any of the beam coupling schemes and for using the radiation as a diagnostic tool in research.

3.3.2 Millimeter Wave Techniques - A.W. Swago

3.3.2.1 Crystal Multipliers

Several more necked-down, straight-line multipliers for 8 mm drive were electroformed during this interval. These were made with different spacings, in an attempt to emphasize various harmonic numbers. Two were assembled, and were tried with various combinations of E-H plane tuners and dielectric phase shifters of the type described in the last quarterly report. Although complete data were not taken, it was found that, while the desired wide range of frequency insensitivity had been achieved, the efficiency at all points was relatively poor. Use of a commercial 1N53 cartridge as a plug-in multiplier agent gave results approximately comparable with whisker-crystal combinations built directly into the guide.

While these results have been essentially discouraging, there still remain one or two assembly combinations which have not been tried. Tests on these will be carried out before any attempt is made to transfer efforts to entirely different types of multiplier construction. (See 3.3.2.2)

Mandrels were designed, and necked-down guide sections in the RG-99/U guide size have been electroformed. The attempt here will be to multiply from 4 mm fundamental power to 2 and 1 mm by using second, and third, or possibly fourth harmonics. An Amperex type DX151 tube has been ordered for use as the driving source for this multiplier, but delivery is not expected until next quarter. In the interim, a classified tube will be used. If the attempt to miniaturize the 1N53 cartridge is successful, use of these packaged diodes as multiplier elements will be tried.

3.3.2.2 Frequency Multiplier Considerations

In reviewing the efforts expended on crystal multipliers by this group, the question arose as to what might be the limiting efficiency to be reached by non-linear resistive elements. Possible analog circuits

for several multiplier constructions were drawn, and one which could represent essentially two types, including the present straight-line version, was considered in more detail. The analog circuit is sketched in Fig. 34.

FIGURE 34 ANALOG CIRCUIT

In the actual multiplier, power is coupled into the 8 mm structure, which can be tuned so that maximum power can be transferred to the whisker for further transmission to the crystal diode junction. The current flowing through the whisker not only transfers the 8 mm power to the crystal, but harmonics present then radiate into a tunable harmonic structure. In the analog, the two tanks in series represent the 8 mm and harmonic systems as reflected back to the whisker, which then forms a series path with the crystal. In the analog circuit, it was decided to use about 1500 cps as the fundamental frequency, and the tanks were constructed with the highest-Q coils available. A 1N56-A crystal was chosen for maximum current capacity. It was assumed that although the characteristics would not agree with the diodes actually in use, its operation would not be radically different. No bias was used. Only two tests were run with this circuit before the end of this interval, one with the tanks tuned to precisely the fundamental and second harmonic frequencies, the other with the harmonic tank tuned to give the best harmonic voltage waveform as viewed on an oscilloscope. The results were not significantly different in the two cases, with the second harmonic power being about 13 db below the fundamental.

It is planned to again check this analog circuit to study the effects on conversion efficiency obtained by varying the effective shunt resistance

of the tanks, and by using bias.

When the tank was tuned to a higher harmonic, the fifth through the eighth, for example, it was found that the resistive effect of the crystal during the half cycle of fundamental conduction so lowered the Q of the harmonic tank as to prevent oscillation at the harmonic frequency during that half cycle. However, the 13 db figure obtained suggests that with crystal multipliers, the 10 db conversion efficiency sometimes obtained by other groups under optimum conditions may be approaching a practical limit with the multiplier configurations presently used.

If a mathematical analysis of the analog circuit shown in Fig. 34 is attempted under periodic boundary conditions, the system determinant yields a fourth degree polynomial. Based on experience, and assuming oscillatory conditions, the types of roots may be guessed, so that roots may be extracted. These become so involved with respect to any particular parameter, however, that effects of its variation cannot be clearly seen. Hence, this approach was abandoned.

In other high-order multiplying systems, for example, harmonic cavities driven by rebatron beams, the overall energy will also vary exponentially. Since this represents an amplitude variation, with presence of a discrete band of frequencies, the signal extractable at a given "harmonic frequency" may not necessarily be directly related to the power actually delivered at this frequency, and may differ with expected values obtained from Fourier series analysis.

The possibility of checking various analog configurations, followed by attempts to synthesize microwave equivalents, may well point to ways of improving conversion efficiency. If, in addition, the non-linearity of the crystal element is included, however, the problem becomes one of non-linear mechanics, and the mathematical processes of handling the problem may become extremely cumbersome.

For the several reasons above, therefore, the advisability of carrying out an overall study of multiplier circuits using an electronic analog computer, recently obtained by the Electrical Engineering Department, is being considered at the present time. The results obtainable from such a study will be judged against time required for programming as well as actual computation time before a firm decision to proceed is made.

3.3.2.3 Other Components for 1 and 2 mm Wavelengths

During this interval, tapered transition sections were made for junctions between RG-96/U and RG-99/U guide sizes to the "1 mm" guide (0.049 inch $\times$ 0.022 inch I.D.) adopted in this laboratory. This completes the group contemplated, so that transitions are now available from 8 mm to 4, 2, and 1 mm, and from 4 mm to 2 and 1 mm.

A tunable shorting plunger for the 1 mm guide, using differential screw action for slow tuning and spring loading to prevent backlash, has been designed and constructed. Minimum size and weight were also made a principle design factor. Since this element has not yet been properly tested, further details will be withheld until the end of the next interval.

3.3.3 Bolometers, and Crystal Detectors - J. Stafford

In this past quarter, the design and construction of suitable detectors for 1, 2, and 4 mm wavelengths and associated equipment has been continued. The main areas of effort have been centered on construction of:

- a. Bolometer mounts
- b. Crystal mounts
- c. Coherent circuits.

3.3.3.1 Bolometer Mounts

In order to obtain a reasonably accurate indication of microwave power, a device with a square law response is to be sought. It is believed that the bolometer is among the devices which more nearly approximate this requirement for a given range of incident power. In addition, since the temperature sensitive wire has a response which is proportional to the heat capacity of the wire, the sensitivity is proportional to the volume or mass of the wire.

$$\frac{1}{r_T} \frac{\partial^2 T}{\partial z^2} + (g - \alpha) = c_v \rho \Delta V \frac{\partial T}{\partial t}$$

where

r_T = thermal resistivity

T = temperature (absolute)

z = coordinate along which wire lies

g = power dissipated

a = power reradiated
 c_v = specific heat capacity
 ρ = density of wire
 ΔV = volume of wire
 t = time,

Consequently, it appears feasible that for a small (~ 16 μ inch) wire, the sensitivity could very well exceed that of a crystal detector.

Also, one is always questioning the degree of sensitivity of a crystal. No absolute method has been determined to evaluate the relative sensitivities of two identical crystals, other than a substitution method. In the case of a bolometer, however, the sensitivity should remain the same from one element to the other, providing there is continuity through the element.

Originally, work began using 50 μ inch Wollaston wire already on hand. The two biggest problems quite naturally are (a) building a suitable mount, and (b) etching away the silver jacket without breaking the remaining platinum core.

A series of three mounts have been built and tried. The first (Fig. 35) is essentially an in-guide construction where the wire is secured on one of the wide guide walls. It is then passed through the other wall, being insulated with a glass sleeve, then through a teflon block, and finally it is fastened to the center conductor of a BNC panel connector. These pieces are then bolted to a brass block as shown. This type of mount proved to be inadequate because of the inability to conveniently etch the wire without breaking it.

A second mount, of a wafer type rather than an in-guide type of construction, was then used (see Fig. 36). This is similar to the commercially available mounts for 4 and 8 mm bolometers. The wire was etched using a micro-manipulator, carrying drops of acid on a glass rod. Using this method, a 50 μ inch bolometer was built and tested. When compared with a commercial bolometer, the relative sensitivity was found to be ~ -15 db. When compared with a 1N53 crystal known to be quite sensitive, the relative sensitivity was found to be ~ -14 db. This bolometer had a cold resistance of ~ 100 ohms as compared to the commercial

FIGURE 35 SCHEMATIC OF FIRST BOLOMETER MOUNT USED.
(Although rigidity is attained here, cumbersome etching procedures caused this mount to be discarded.)

FIGURE 36 FLEXIBLE MICA MOUNT SIMILAR TO COMMERCIAL BOLOMETERS
(This mount is adequate for larger wires but was found to be too pliable for use with small wires (16 μ inch.)

bolometer's resistance of 200 ohms. A ratio of 2:1 in resistance indicates a ratio of diameters to be .707:1 or indicates that the commercial bolometer has a wire diameter of $\sim 34 \mu$ inches and should be expected to have a greater sensitivity.

In the above measurements the experimental bolometer gave an indication under matched (E-H plane tuner) conditions of 4 db over noise. An interesting feature of this test was the apparently greater sensitivity of a bolometer when compared with the crystal. When this construction was attempted using a 16μ inch wire, it was found that the pliability of the mica sheet considerably reduced the life of a wire, if not rendering its construction impossible.

The third mount is of a construction similar to the block and wafer used at the Bell Telephone Laboratories for testing crystals. (Fig. 37.) The wire is passed through the teflon wafer, and through the waveguide insert as with the first mount, and fixed to both the bottom of the waveguide and the termination pin with silver paint. Thus far, no 16μ inch bolometer has been constructed because of one fault or another with the etching technique. The most serious problem has been the violent reaction between the copper waveguide and the etching acid, breaking the fine wire before it is completely etched. The gold plating will not withstand the presence of the acid for a duration of even 30 seconds, the approximate time required to dissolve the silver jacket.

It is believed that this holder is the most desirable of the three since it combines both the in-guide and wafer types of construction, thereby utilizing the properties of rigid construction along with an expendable, easily replaced unit.

Figure 38 is a picture of the stand used in etching the thin wires. The wafer is clamped into the vise over the center hole. Acid is then forced up through the hole. This action can be viewed using a 150 power microscope.

3.3.3.2 Crystal Mounts.

With a view to providing a more compact crystal detector than the previously used detectors requiring a differential screw drive, an effort was made to reduce a 1N53 cartridge by a factor of two or three. Not all dimensions have been reduced by this factor because of the limitation of machine shop capabilities. Crystal dicings already on hand were prepared

FIGURE 37 THIRD TYPE OF MOUNT SIMILAR TO THE ONE USED AT BELL TELEPHONE LABORATORIES. (Rigidity and easy accessibility for etching make this mount the most desirable.)

FIGURE 38 STAND USED IN ETCHING THIN WIRES

Stand in center foreground is one used for etching bolometers. Also shown is stand used to adjust the height of the acid, and the 150 power microscope used to view etching. Sufficient light is carried through column of acid.

FIGURE 39 FINAL ASSEMBLY JIG

Jig used in final assembly of miniature crystal cartridges is shown in center foreground; also shown is assembly lathe and source for 60 cycle sweep voltage. Note crystal in assembly jig.

and more were ordered.

The three biggest problems involved were (a) jigging and assembly, (b) suitably preparing the whisker (tungsten), and (c) seating the whisker permanently into the crystal.

Jigging was facilitated by procuring a tailstock and collets for a jeweler's lathe. The headstock and bed were found among some discarded machinery. A final assembly jig (Fig. 39) was made by Mr. Lowe in the machine shop.

At first, an attempt to solder the tungsten whisker to the brass post was made. This method was both messy and tedious. Finally the whisker was spot-welded onto the side of the post instead of on the top, as is usually done. The insulating bead is then pushed onto the post and the whisker is formed and pointed.

The final assembly is completed by driving the crystal into the pointed whisker while sweeping the unit with a 60 cycle voltage. Upon attaining a suitable contact, i.e., where the forward transmission is suitably steep, the contact is made firm by imparting a solid blow to the jig. The mechanism of this action is not completely understood, but the results indicate an improvement. A comparison with a 1N53 cartridge when both are being swept at a 60 cycle rate is seen in Fig. 40. This new cartridge using 1N26 material has been inserted into a suitable waveguide mount and tested at 5 mm. The overall sensitivity is approximately one-fourth that of a 1N53 crystal inserted in the same circuit.

It is expected that a more sensitive crystal can be built using 1N53 material, preparing the surface more carefully, and taking greater pains while preparing the whisker point. Also, the final assembly jig will be modified so that the assembly can take place with 5 mm power incident on the cartridge.

3.3.3.3 Coherent Circuit

A coherent detector using switching techniques has been designed and is in the process of being built. This circuit originated at the Stanford Research Institute and was reported to be capable of detecting signals 30 to 40 db below the noise level. The circuit was modified so as to be more adaptable to our specific needs. It is expected that this circuit will be finished and tested in the following quarter.

FIGURE 40. 60 CYCLE CHARACTERISTIC OF MINIATURE
CRYSTAL CARTRIDGE USING 1N26 MATERIAL
(TOP) AND SIMILAR CURVE, TO SAME SCALE,
FOR 1N53 CRYSTAL (BOTTOM)

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QUARTERLY PROGRESS REPORT

on

RESEARCH AND INVESTIGATION
LEADING TO METHODS OF
GENERATING AND DETECTING
RADIATION IN THE
100 TO 1000 MICRON WAVELENGTH
RANGE OF THE SPECTRUM

Contract No. AT(11-1-392)
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by

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1. INTRODUCTION - P.D. Coleman

1.1 Preface

This is the seventh quarterly report for Contract No. AT(11-1)-392 on "Research and Investigation Leading to Methods of Generating and Detecting Radiation in the 100 to 1000 Micron Wavelength Range of the Spectrum." This report covers the period 1 September 1957 to 1 December 1957.

1.2 Purpose

The purpose of this research is twofold:

- a) To uncover new principles or techniques from which a source of high pulsed power for the 100-1000 micron wavelength range of the spectrum can be developed. Ideally it is desirable that the source will possess a line spectrum.
- b) To investigate suitable detecting and measuring techniques for evaluating and utilization as a diagnostic tool for physical research.

2. GENERAL FACTUAL DATA - P.D. Coleman

2.1 Approach to the Generation Problem - Frequency Multiplication with a Non-Linear Element

The generation of electromagnetic radiation in the wavelength range 0.1 to 3 millimeters is as yet an unsolved problem. Moreover, even an idea that might lead to a prime source of radiation has yet to be suggested as far as this author is aware. This does not mean that research towards a source is not possible or fruitful at the present time.

It is well known that non-linear effects lead to the generation of harmonic and/or subharmonic frequencies. A number of physics phenomena show strong non-linear properties in the millimeter wavelength range, for example: (1) a silicon crystal rectifier, (2) a field emitter, (3) the magnetization of a ferrite, (4) a gas discharge, (5) an electron beam, etc. If the appropriate circuits or experimental arrangements incorporating these elements could be devised, and could be driven, for example, by a high power level eight millimeter wavelength electron tube, there are reasons to believe that low millimeter and submillimeter wavelength signals could be produced.

The synthesis of a non-linear circuit does not appear to be an easy task. What is ideally desired is an arrangement that can be driven at a frequency f_0 but which has dissipation only at a given frequency nf_0 , thereby achieving a gain of one in multiplying from f_0 to nf_0 . It is doubtful if this ideal circuit can be synthesized, but there is every reason to believe that the dissipation at a given harmonic frequency could be accentuated over all others. Circuits presently used--for example, one employing a silicon crystal--give a second harmonic power 15 to 20 db down from the fundamental drive power, the third harmonic power 25 to 30 db down, etc. It has not been demonstrated that these circuits are anywhere near optimum nor that conversion gains far greater than those presently obtained are theoretically possible.

It should be pointed out that a study of the non-linear element alone is not sufficient. For example, consider a field emitter whose law is $i = A \exp(-B/e)$. It is an elementary numerical problem to compute i versus e and to determine the Fourier series expansion coefficients for i under

period voltage excitation e . The problem to be solved is how to extract the maximum power at a specified harmonic frequency nf_0 . This later problem requires some sort of input coupling circuit from a generator at frequency f_0 and an output coupling circuit at frequency nf_0 to a load. Just how to make these coupling circuits optimum is the heart of the problem and one which appears to have no straightforward solution.

The present program being followed by the Ultramicrowave Group is based entirely on frequency multiplication using a non-linear element. Our major effort has been on (1) silicon crystal multipliers for achieving low power level CW millimeter signals for bench testing and development of components, and (2) megavolt electronics electron beam multipliers for producing high pulsed power level signals. More recently, work has been initiated on field emitter multipliers and plans are underway to investigate gas discharge and ferrite multipliers. All these attacks on the generation problem have in common the task of synthesizing an optimum non-linear circuit with maximum frequency conversion from f_0 to nf_0 .

2.2 Bunched Megavolt Beams as Non-Linear Elements for Use in Megavolt Electronics

A schematic drawing of a megavolt electronics millimeter wave generation system, using an electron beam as a non-linear element for frequency multiplication, is shown in Fig. 1. In this system, a high power microwave tube source at frequency f_0 drives a relativistic electron bunching accelerator, called a REBATRON, which converts a low voltage DC beam into a bunched megavolt beam containing high current harmonic frequencies of the driving source. This harmonic beam, in turn, drives a coupling device which converts a part of the beam kinetic energy into RF energy at frequency nf_0 .

A program on megavolt electronics, as seen from Fig. 1, involves three phases: (1) the production and evaluation of the bunched megavolt beam, (2) the study of beam coupling structures, and (3) the development of detectors and measuring components.

The problem of creating a high energy bunched electron beam has been initially solved in a very compact relativistic electron accelerator and buncher, called a REBATRON, which is illustrated in Fig. 2. This device consists of a single TM_{010} mode microwave cavity driven by a high power magnetron. A simple prebunching system is used to inject electrons into the accelerator. This system consists of a Pierce gun, modulating cavity, and drift distance arranged to give the entrance beam a desirable velocity-phase relationship to achieve good bunching in the accelerating cavity.

FIGURE 1 MEGAVOLT ELECTRONICS SYSTEM

FIGURE 2 REBATRON STRUCTURE

Theoretical calculations have given a computed harmonic content in the exit beam of appreciable value to as high as the 1000th term in the Fourier series representation of the current. Furthermore, the velocity spectrum of the accelerated electrons is sufficiently peaked that the beam can be quite accurately represented as a traveling current wave of the form

$$i(t, z) = \sum_s I_s \cos 2\pi s f_0 (t - z/v) \quad (1)$$

where

$$I_s \approx 2 I_0$$

and

$$v \approx c.$$

The theoretical calculations are of necessity somewhat idealized so that, coupled with the tolerance problem, it is hoped that in practice it will be feasible to use harmonics up through the 100th. Power at the 35th harmonic of the S-band rebatron has already been achieved, with work in progress to extend the useable harmonic power to one millimeter wavelength.

To produce power below one millimeter wavelength, an X-band (3 cm) bunching accelerator is being developed. This device will use the rebatron structure followed by a short linear accelerator section to accelerate the bunched beam into the 1 to 3 mev range. The linear accelerator section is necessary since sufficient voltage cannot be developed across a TM₀₁₀ mode cavity at X-band to achieve megavolt beams without voltage breakdown in the structure.

FIGURE 3 X-BAND BUNCHING ACCELERATOR

2.3 Megavolt Coupling Structure Research

The coupling structure work is along two lines: (1) the excitation of the higher order modes of a system to solve the physical size limitation problem, and (2) non-resonant Cerenkov structures.

It is well known that a structure oscillating in a higher order mode can be physically large compared to the resonant wavelength. For example, in the case of the TM_{omn} mode cylindrical cavity shown in Fig. 4 by using large values of the indices m and n , it is seen that D/λ_0 and L/λ_0 can be made much greater than one.

$$\left(\frac{D}{\lambda_0}\right)^2 = \left(\frac{r_{om}}{\pi}\right)^2 + \left(\frac{nD}{2L}\right)^2 \quad (2)$$

$$\frac{v_p}{c} = \sqrt{1 + \left(\frac{r_{om} 2L}{\pi n D}\right)^2} \quad (3)$$

$$k_+ = \frac{1}{2} \frac{\sin \left[\frac{\pi L}{\lambda_0} \left(\frac{c}{v} - \frac{c}{v_p} \right) \right]}{\left[\frac{\pi L}{\lambda_0} \left(\frac{c}{v} - \frac{c}{v_p} \right) \right]} \quad (4)$$

FIGURE 4 EXCITATION OF TM_{omn} MODES OF CYLINDRICAL METAL CAVITY

Two problems are involved in exciting higher order mode structures: (1) the mode interference problem, and (2) the coupling problem, as seen from Eqs. 3 and 4. The power given up by the beam can be expressed as

$$\mathcal{P} \approx \frac{1}{2} (I_s k_+)^2 R \quad (5)$$

where k_+ is the coupling coefficient given by Eq. 4, and R is the circuit interaction resistance. Unless $v \approx c$, very little power could be extracted from a beam using the TM_{0mn} metal structure shown in Fig. 4.

However, using a beam velocity $v \geq 0.93c$, it has been shown that modes up to the $TM_{02(10)}$ and $TM_{03(10)}$ are practical without using mode suppression techniques. Thus a simple structure, large enough to be fabricated conveniently, can be made to produce radiation below one millimeter.

The current work is directed towards finding a structure whose phase velocity is in the range $0.93c \leq v_p \leq c$ and whose higher order modes can be well separated so as not to cause mode interference. A structure which shows considerable promise in this direction is the dielectric cavity shown in Fig. 5.

FIGURE 5 DIELECTRIC HARMODOTRON

This structure behaves as a high Q cavity only for those modes whose phase velocity is less than the velocity of light c , so that some mode suppression is inherent in the device. Also, since there are two additional parameters b and ϵ associated with this device as compared to the metal structure, additional mode separation can be achieved.

Work is in progress in evaluating the mode properties (a very tedious numerical task) of these structures and the power output that

can be achieved. Initial experiments have checked very well with theory, using a $TM_{01(13)}$ mode at eight millimeters wavelength.

The Cerenkov structure being investigated is a split dielectric cone, as shown in Fig. 6. The cone has been split into two equal sections, the

FIGURE 6 CERENKOV RADIATOR

one section then displaced a distance D relative to the first, to destroy part of the circular symmetry and make the radiator end fire.

The advantage of a megavolt beam is again evident when one examines the E_z field component in the axial hole traversed by the beam.

$$E_z = E_0 \left\{ a_n I_0(Kr) + \frac{\rho_n}{K^2 \epsilon_0} \right\} e^{in\omega_0(t-z/v)} \quad (6)$$

where

$$K = \frac{2\pi}{\beta\lambda_0} \sqrt{1 - \beta^2}$$

and

$$v = \beta c.$$

As $\beta \rightarrow 1$, $K \rightarrow 0$ and the field becomes more uniform in the r direction, so that the beam does not need to pass close to the dielectric.

2.4 Detectors and Components

The present aim of this work is to develop a set of two and one millimeter components around 0.075×0.034 inch and 0.049×0.022 inch guide, for use in microwave diagnostics of gaseous plasmas.

The signal source for testing components has been the silicon crystal cross guide multiplier, using QK288 and EMI (R9521) eight millimeter klystrons as drivers. Numerous new mechanical and electrical designs are being tried to improve these multipliers to increase their output power. An Amperex DX-151 four millimeter klystron and an Elliott Brothers VX 9206 eight millimeter klystron are being secured for drivers of new multiplying devices.

The machining and mechanical problems of fabricating one millimeter wavelength components have been largely solved. What is needed is better signal sources so that the electrical designs can be improved and better evaluated.

2.5 Present Status of the Work

2.5.1 Rebatron Research

2.5.1.1 S-Band Rebatron

A very important practical technical rebatron problem has been solved this quarter, the problem of feeding a pulsed magnetron into a high Q (greater than 10,000) circuit. The magnetron is ideally suited for a rebatron driving source in that it (1) delivers high pulsed power of the order of a megawatt, (2) is physically very compact in size, and (3) the required pulsed power supply (8 kv at 300 a) can be packaged in a small unit with no difficult voltage or components problems. Its only drawback has been that it will not fire directly into a high Q circuit. In the past, a series Tee stabilizing circuit has been used, which results in more than half of the magnetron power being dissipated in a stabilizing resistor or load. To make up for this loss, a second magnetron has been added to the circuit, thereby doubling the equipment requirements.

This quarter a high power ferrite isolator has been secured from Cascade Research which, when incorporated into the appropriate microwave circuit, permitted practically the entire magnetron power to be fed directly into our high Q accelerating cavity. This achievement will permit us to package our rebatrons in a portable system with size on the order of

a half relay rack. More important, this more efficient use of magnetron power should permit us to build a K-band rebatron-accelerator system, where high power is at a premium, in the near future.

2.5.1.2 X-Band Rebatron

The PACE analogue computer has been programmed, and curves of particle displacement and velocity have been computed for field strengths from 50 to 500 kv/cm for injection velocities ranging from 0.24 c to 0.40 c. These calculations will permit us to design the rebatron section of our 3 cm bunching accelerator. The linear accelerator section, shown in Figure 3, has not as yet been programmed. It is planned to carry out this computation while the rebatron section is under construction, since the two sections can be designed somewhat independently.

2.5.2 Beam Coupling Schemes

Work on coupling schemes this quarter was limited entirely to the dielectric harmodotron. The problems involved with the excitation of any higher order mode device are (1) evaluation of the mode properties of the structure, (2) calculation of the power output, (3) design of the structure to obtain the maximum output power with the minimum of mode interference, and (4) experimental verification.

This quarter the calculation of the TE modes of teflon cavities has been completed so that a good comparison of the TM and TE modes of metal and dielectric cavities can now be made.

Preparations have been made to perform the next dielectric harmodotron experiment at 5.18 millimeters where the components can be thoroughly bench tested.

2.5.3 Detecting and Measuring Techniques

Crystal multipliers involve (1) the synthesis of a non-linear frequency multiplying circuit, and (2) a difficult mechanical fabrication problem. Up until this quarter, our effort on these multipliers has been predominately concerned with mechanical designs. We have been trying cross-guide, straight guide, tapered guide, and built-in guide crystal, or coax cartridge crystal, and other arrangements in an effort to simplify some of the mechanical problems. While all of the fabrication problems are not solved, we can now build almost anything we can design. The next step is to take a more critical look at the electrical design problems.

Some time was spent this quarter on examining some analog circuits in order to attack the frequency conversion efficiency problem. The first circuit tried gave a second harmonic power about 13 db below the fundamental, a value comparable to the best crystal circuits now being used.

Work was initiated this quarter on a 16 microinch bolometer detector for our 0.049×0.022 inch waveguide. Designing a mount whereby the Wollaston wire can be etched directly in the mount is a bit of a problem. Several ideas were tried without success. However, it is believed that the detector can be made with further improvements in techniques.

A 1N53 coax crystal is physically too large to be placed across a 0.049×0.022 inch guide. What is needed is a crystal cartridge roughly one third the size of a 1N53. Several scaled down crystal cartridges were constructed to examine the fabrication problems involved. At five millimeters, these crystals in an appropriate mount, had a sensitivity roughly one-fourth that of a 1N53. However, by better crystal surface treatment, it is believed that the sensitivities can be made equal.

2.6 Personnel

The present staff assigned to Contract AT(11-1)-392 includes:

<u>Supervision</u>	<u>Percent Time</u>	<u>Date Assigned to contract</u>
Paul D. Coleman, Professor Director	66 2/3	1 April 1956
<u>Staff</u>		
Andrew Swago, Instructor	50	1 April 1956
<u>Research Associates and Assistants</u>		
Harold Spuhler, Research Assistant	75	1 September 1956
Richard Kenyon, Research Assistant	75	1 April 1956
Richard Becker, Research Assistant	100	1 December 1956
Joseph Stafford, Research Assistant	50	1 February 1957
<u>Electronic Technicians</u>		
Kenneth Bartlett, Sr. Elec. Tech.	80	1 April 1956
Allen B. Wilson, Sr. Elec. Tech.	33	1 April 1956
Garry Paddick, Student (Hourly)	(15 Hrs. week)	1 June 1956
<u>Shop Technicians</u>		
John F. Lowe, Instrument Maker	100	1 April 1956
Lewis Claybaugh, Senior Laboratory Mechanic	75	1 March 1957

Clerks

Donald Pritchard	25	1 April 1956
Richard Ripper	25	1 April 1956

2.7 Papers, Reports, Publications, Visits2.7.1 Quarterly Reports

<u>Title</u>	<u>Report Period</u>
Quarterly Report No. 1	1 March to 1 June 1956
Quarterly Report No. 2	1 June to 1 September 1956
Quarterly Report No. 3	1 September to 1 December 1956
Quarterly Report No. 4	1 December to 1 March 1957
Quarterly Report No. 5	1 March to 1 June 1957
Quarterly Report No. 6	1 June to 1 September 1957

2.7.2 Technical Reports

"The Harmodotron--A Beam Harmonic Higher Order Mode Device for Producing Millimeter and Submillimeter Waves," M.D. Sirkis, Technical Report No. 1, 10 September 1956.

2.7.3 Conference Papers

"Megavolt Electronics and the Submillimeter Wave Problem," presented by P.D. Coleman at the Fourteenth Annual Conference on Electron Tube Research, June 1956, Boulder, Colorado.

"Megavolt Electronics Millimeter Wave Coupling Structure Research at the University of Illinois," presented by P.D. Coleman at the Tri-Service Millimeter Wave Symposium in September 1957 at Fort Monmouth, N.J.

2.7.4 Papers Accepted for Publication

The following papers were published in the September 1957 issue of the Journal of Applied Physics

1. "The Theory of the Rebatron--a Relativistic Electron Bunching Accelerator for Use in Megavolt Electronics," P.D. Coleman.
2. "The Design and Evaluation of a 3 kmc Rebatron," I. Kaufman and P.D. Coleman (this paper was jointly supported by Contracts AT(11-1)-392 and AF18(603)-62.
3. "The Harmodotron--A Megavolt Electronics Millimeter and Submillimeter Wave Generator," M.D. Sirkis and P.D. Coleman.

The following paper has been accepted for publication in the IRE Trans., PGED:

"Dielectric Slow-Wave Structures for the Generation of Power at Millimeter and Submillimeter Wavelengths," R.H. Pantell, P.D. Coleman, R.C. Becker.

2.7.5 Visits and Conferences

P. Coleman visited Dr. Mark Heald at Princeton and Mr. Donald Slager at Los Alamos during the month of September to discuss millimeter waves and plasma diagnostics.

Dr. Mark Heald visited the Ultramicrowave Group in October to see our work first hand and to discuss plans for mutual assistance.

P. Coleman and Dr. Charles Wharton of Livermore had occasion to discuss recent progress during the NEC meeting in Chicago in October.

P. Coleman visited Dr. A.E. Ruark and Dr. H. Roderick in Washington, D.C. in September to review the past work on the contract and to discuss future plans.

3. DETAILED FACTUAL DATA

3.1 Rebatron

3.1.1 Purpose

The objective of this phase of the program is the design and development of a practical, compact, portable rebatron. There are four subphases to this work.

1. Microwave circuit problem
2. Electron injection problem
3. Electron trajectory calculations
4. Electronic instrumentation problem.

3.1.2 Electron Injection Problem - R. Kenyon

3.1.2.1 Purpose

The aim of this work is to investigate the electron dynamics problem in the rebatron from the point of view of increasing the accelerated current to its largest practical value.

3.1.2.2 Present Status of the Accelerating Cavity

Because the use of the E-plane bend made it impossible to change the size of the coupling hole once the cavity was brazed together, a test cavity was built without the bend for this purpose. For a single port cavity, the correct coupling hole size will give a 1 to 1 VSWR (strictly speaking, it is necessary to have a small amount of power reflected to the magnetron to lock the magnetron on the cavity frequency). By using the side-band technique with a frequency stabilized oscillator, the coupling hole diameter was determined to be 23/32 inch for a SWR of less than 1 db. This was for the test cavity without the E-plane bend. This coupling hole size was then used for the cavity to be used in the rebatron and was brazed together, including the E-plane bend.

The cavity was then checked experimentally to determine whether the 23/32 inch coupling hole diameter was indeed the correct size. First, the resonant frequency was determined to be 2843.5 mc/s by using a 60 cps modulated klystron, a magic-tee and a co-axial wave meter. The frequency stabilized oscillator was then set to 2844.1 mc/s and the lower side-band was used to measure the curves shown in Fig. 7. The setup also included the demountable vacuum seal, which is necessary in the rebatron, so that the curves in Fig. 7 include the effect of the coupling hole, the E-plane bend, and the vacuum seal on the match. From Fig. 7, the following quantities are known: SWR on resonance is less than 1 db and is overcoupled; the position of the minimum on resonance is 3.40 cm on the generator side of the

FIGURE 7 SWR AND POSITION OF MINIMUM VS. SIDE-BAND FREQUENCY

vacuum seal flange; $Q_L \approx 12,000$.

It may be noticed that the resonant frequency of this cavity is about 60 mc/s higher than the previous cavities that have been constructed. This is due, as shown in Fig. 8, to the concave entrance end wall.

This completes the low-power measurements on the cavity and it is now ready for testing with the high-power microwave circuit.

3.1.2.3. Present Status of the Microwave Circuit

With the receipt of a high power ferrite isolator on loan from Cascade Research Corporation, the microwave circuit problem has taken on a new aspect. At present, tests are being carried on to determine whether this isolator can be used to replace the stabilizing-load-H-plane-tee combination. The present status of these tests will be discussed in Section 3.1.4.

3.1.2.4 Present Status of the Injection Tube

Two high voltage vacuum bushings were received during this quarter for testing. Figure 9 shows one of the terminals brazed into a copper base plate for use in an injection tube. It has a number of physical advantages over the present gun which utilizes a metal-to-glass seal at the base plate and a porous ceramic disc for mounting the electrodes. First, the metal-to-glass seal is eliminated since the bushing is vacuum tight; second, it can be high temperature brazed which provides a clean, leak-free joint; third, it is a glazed ceramic, which makes it possible to keep it clean.

A test was performed with this bushing by placing it inside one of the present injection tube barrels, evacuating it, and applying pulse voltage to the mounting posts. Corona was noticed at the mounting posts at about 29 kv and arcing at the rear of the tube (in air) started at about 30 kv. The bushing, therefore, is not much better, from a breakdown standpoint, than the present design, since the latter has been used up to 27 kv. Its only advantages are the physical ones previously mentioned. An attempt will be made to obtain a bushing suitable to 40 kv.

3.1.2.5 Present Status of Portable Vacuum Station

Except for a few minor items, the control panels for the front of the table are finished. Provisions for supplying water and power to the table have also been completed and the internal power wiring has been completed. The rest of the work necessary to complete the table, such as the internal

FIGURE 8 SINGLE PORT ACCELERATING CAVITY DIMENSIONS

FIGURE 9 HIGH VOLTAGE BUSHING

FIGURE 10 ANALOG COMPUTER INSTALLATION

water supply, placement of the vacuum system, placement of the pulse transformers, etc., is contingent upon the location of the accelerating cavity, which is in turn contingent upon the method of magnetron stabilization to be used (See Section 3.1.4).

3.1.3 Rebatron Design above 3 kmc/s - H. Spuhler

3.1.3.1 Purpose

The purpose of this phase of the project is two-fold:

1. To investigate the problems involved in operation of a rebatron at frequencies above 3 kmc/s and to determine the highest frequency useable, considering components presently available.
2. To construct and test a rebatron operating at the highest frequency above 3 kmc/s for which design factors are practical.

3.1.3.2 Present Status

Particle displacement and relative velocity curves have been obtained using the PACE Analog Computer. The range in peak axial electric field covered from 50 to 500 kv/cm. The range in injection relative velocity covered from 0.24 to 0.40. The program was checked using results for the 10 cm rebatron obtained using the ILLIAC Digital Computer. Estimated accuracy for the test problem was 0.5% in the region of interest about π radians for the cavity phase.

Figures 10 and 11 show the analog computer installation and a closeup of the data curves as obtained from the Variplotter. The two curves shown represent electron displacement along the cavity axis and electron relative velocity, both drawn using cavity phase angle for the abscissa variable. Since the proportionality constant $H = \frac{e E_0}{\omega m_0 c}$ depends in ratio of E_0 to ω , the families of curves obtained for various values of H provide a universal set for electron trajectories through cavities operating in the TM_{010} mode. Thus the data obtained will be used in the consideration of the K-band rebatron as well as for the X-band design.

The form in which the data are presented provides a relatively simple determination of proper cavity dimensions in contrast to the Illiac data. The digital program involves integration to a fixed cavity length, which must be chosen as one of the preset parameters. In both cases the families of ideal injection velocity distribution curves, etc., must be manually plotted.

FIGURE 11 CLOSE-UP OF DATA CURVES OBTAINED FROM THE VARIPLOTTER

Work is now in progress on plotting ideal injection velocity distributions for the various conditions so that bunch and momentum distributions may be optimized. From results to date it seems that, for an operating frequency of 9.3 kmc/s, a cavity length of 1.08 cm with input power of 0.1 megawatt will be close to optimum. For this condition, peak axial field will be 498 kv/cm, a value which should not exceed breakdown criteria for the cavity when properly finished and evacuated.

With the average output relative velocity assumed to be 0.8, a rough calculation indicates that space bunching to within 0.1 mm will be obtained if the ideal injection velocity distribution can be matched so that the output phase variation is less than 0.025 radian or about 1.45 degrees. While results for the modulating cavity have not been plotted as yet, experience with the 10 cm rebatron indicates this is practical. Velocity variation within the bunch should be very small since the ejection velocity changes are small in this region. No momentum calculations have been made to date.

Work on programming for the tapered section of the linear accelerator has been deferred until the rebatron design has been completed so that construction of the 3 cm rebatron may be under way while the accelerator calculations are in progress.

Because of the very successful results obtained in using a ferrite isolator for magnetron stabilization, such a system will be used rather than one using a waveguide tee or gas-tube switch. The mechanical design aspects of the isolator system are much simpler and experimental results (reported in Section 3.1.4) indicate that this is the most efficient way to couple a magnetron to a high-Q cavity in a pulsed system. Work on the gas-tube switch and waveguide tee methods of stabilization has been discontinued.

The last phase of the rebatron design is that of the Pierce gun beam injection system. Present plans are to use the present gun design modified to place the minimum spot at the center of the accelerating cavity. Work on this phase will begin after designs have been completed for the modulating and accelerating cavities.

3.1.4 Magnetron Stabilization - H. Spuhler, R. Kenyon

One of the several problems involved in rebatron design has been the stabilization of the magnetron oscillator used to drive the high-Q accelerating cavity. In the past, stabilization was accomplished by coupling to the cavity through a waveguide tee with its side arm terminated by a matched load. The tees used with the first two machines were designed for a 1:1 power division. Since that time tees having various power ratios have been tested. The highest ratio used was 4:1, that is, 80% of the available power reached the cavity. For this case, however, stabilization was not satisfactory. Since at least 0.8 megawatt at the cavity is required to produce the desired output energy level at 10 cm, a one-magnetron system would require either a more efficient coupling system or a tube having higher available power output.

As indicated in the last report a gas-tube switch was tried. The waveguide tee system was modified by introducing a slotted section between the tee and the matched load. Through the slot an evacuated glass tube was placed with its axis parallel to the electric field. The slot, together with adjustment of the gas pressure in the tube permitted firing of the tube at various intensity levels and at various positions with respect to the reference plane of the tee. Expectations were that a proper choice of operating conditions would permit the tube to fire into the matched load until oscillations had started to build up in the cavity, at which time firing of the gas tube would switch out the load and couple the magnetron directly to the cavity. Initial attempts to secure stabilization in this way were unsuccessful. Operation was intermittent and magnetron moding was excessive. Results indicated the slot should be eliminated and a sealed tube used, together with a shorter line length to the load. Further work in this direction was suspended on receipt of a 10 cm high-power ferrite isolator loaned to the project for experimental use.

With the isolator connected directly to the magnetron output, the cavity was coupled to the isolator through a directional coupler and a phase-shifter which would permit precise adjustment of electrical line length. Rough adjustment of line length was obtained using a short matching section containing a window to permit evacuation of the cavity without sealing the entire guide. Power fed toward the cavity, power delivered to the cavity, and power reflected from the cavity were monitored, using an oscilloscope

to view the pulse envelope. Figures 12 and 13 show the system both with and without the lead shielding in place around the cavity. Since comparison with the performance of the waveguide tee method was to be made, the magnetron operating conditions were kept constant, except for slight tuning adjustments. X-ray yield from the cavity was measured with the radiation monitor placed along the cavity axis at a distance of three inches from the end wall.

To obtain a qualitative performance rating the test was run without means of precise power measurement. In each case, magnetron operating conditions were fixed and the detector tuning and oscilloscope gain unchanged. A small change in phasing was required when the tee system was used in place of the isolator. Pictures of the monitor waveforms and comparative x-ray yield were used to judge relative performance.

The maximum x-ray yield using the isolator was 1.5 r/hour while that obtained using the tee system was only 0.1 r/hour. Figure 14a shows the reflected power pulse for the isolator system below that of the cavity power monitor. The top pair show the cavity power rising exponentially to an essentially flat top, as is necessary for proper operation of the rebatron. The reflected power decays very nearly to the base line, indicating that more than 90% of the power is being delivered to the cavity. The bottom pair shows the reflected power waveform inverted for comparison of the rise and decay times of the pulses.

Figure 14b shows the same waveforms as taken using the waveguide tee for stabilization. The increase in reflected power from the cavity, hence the decrease in power delivered to the cavity, is evident from the shape of the pulse. Also, as previously stated, the x-ray yield decreased from 1.5r/hour to 0.1r/hour. No quantitative data were taken from which to determine the magnitude of the power delivered to the cavity. However, it seems evident that the isolator system is significantly superior in terms of performance as well as mechanical simplicity and convenience.

For this reason quantitative measurements will be made of cavity power using the 10 degree spectroscopy which was constructed for momentum measurements on the other two machines. Momentum measurements will provide a means of determining the field in the cavity, hence the power actually delivered to the cavity. One of the new Pierce guns will be used to provide the beam injected along the cavity axis. The gun and spectroscopy assemblies have been installed and aging of the cathode is now in process.

FIGURE 12 INSTRUMENTATION FOR ISOLATOR TEST

FIGURE 13. MICROWAVE CIRCUIT FOR ISOLATOR TEST

FIGURE 14A MONITOR WAVEFORMS FOR
ISOLATOR STABILIZATION

FIGURE 14B MONITOR WAVEFORMS FOR
THE TEE STABILIZATION

3.2 Beam Coupling Schemes

3.2.1 Purpose

This part of the research work has as its goal the origination of generation schemes using the million volt, bunched electron beam from the rebatron to produce high pulsed power in the 0.1 to 1 mm wavelength region of the electromagnetic spectrum. The general methods of approach to the problem are along two lines:

- 1) Extending existing tube techniques by means of megavolt electronics.
- 2) Using the Doppler and Cerenkov effects in direct radiation devices.

3.2.2 The Slow-Wave Dielectric Harmodotron - R.C. Becker

3.2.2.1 Introduction

During the past interval, analysis of the slow-wave, dielectric, higher order mode resonator has included the computation of the TE mode design curves, plots of the mode patterns, and the preparation of a five millimeter experiment using the rebatron. Detailed theoretical investigation of the general behaviour of this resonant structure is being pursued because its properties are distinct from those of the more conventional cavity resonators, and since its mode separation properties may provide a device which is extremely advantageous in various microwave applications employing resonant cavities. The slow-wave properties of this device make its utilization in beam coupling problems particularly attractive, due to the increased coupling efficiency and greater power output ordinarily attainable. Experimentation continues in an effort to learn more about the actual performance of this structure, and as verification of the theory used to describe its behaviour.

3.2.2.2 Article for Publication

The paper entitled, "Dielectric Slow-Wave Structures for the Generation of Power at Millimeter and Submillimeter Wavelengths," by Richard H. Pantell, Paul D. Coleman, and Richard C. Becker, has been accepted for publication. The article is to appear in the April, 1958, issue of the Transactions on Electron Devices published by the Institute of Radio Engineers, New York.

3.2.2.3 Analysis of the Slow-Wave Dielectric Harmodotron

3.2.2.3.1 Introduction

Theoretical investigation of this device (Fig. 15) during past months has already provided information which was of particular use in applications of the slow-wave dielectric resonator as a beam coupling structure. This has been due to the fact that the primary aim of this investigation is to generate millimeter and submillimeter waves by means of the megavolt electronics technique which directly involves a high energy, tightly bunched electron beam. In such applications the beam passes through the structure along the axis of symmetry and is assumed to be a symmetrical source giving rise to fields which are symmetrical about the axis of symmetry (no ϕ -variation). Thus, only the TM_{omn} modes are of interest in describing the energy exchange between the beam and the resonator under such conditions. Design curves and mode charts, together with power calculations for operation of this device in TM_{omn} modes, have already appeared in previous reports published under this contract.

The true advantage of the slow-wave dielectric resonator as a device which can be designed for negligible mode interference cannot be determined, however, until the investigation of all possible modes which can exist within the structure has been completed. Complementing the TM_{omn} mode information appearing in Technical Progress Report No. 6 (15 September 1957), there appear in this report the TE_{omn} mode charts for this device. These two sets of modes completely describe the field behaviour of this resonant structure when the fields are axially symmetric, that is, when no ϕ -variation exists. Design curves for the TE_{omn} modes are also included, since other microwave applications may require resonance in a TE mode.

Representative field plots describing the behaviour of the fields at the end walls are also presented. Since the output waveguide coupling aperture is located in an end wall, this information permits placement of the output waveguide at the most desirable location. Continuity of these field plots at the boundaries of the dielectric cylinder ($\rho = a, b$) has also served as a check on the validity of certain of the previous power calculations.

FIGURE 15 SLOW-WAVE DIELECTRIC HARMODOTRON

3.2.2.3.2 The TE_{omn} Mode Fields

The procedure for deriving the characteristic equation for the TE_{omn} modes, and obtaining there-from the design curves and the mode charts, is similar to that used in the analysis of the TM_{omn} modes. Because the method involves much detail and is quite lengthy, and since the complete analysis for the TM_{omn} modes already appears in Technical Progress Reports No. 4 (15 March 1957), No. 5 (15 June 1957), and No. 6 (15 September 1957), only a synopsis of the analytical technique will be presented.

Solutions to the wave equations derived from Maxwell's equations are found for the structure pictured in Fig. 15. The general solution is of the form, assuming $e^{j\omega t}$ time dependence,

$$H_{zs}(\rho, \phi, z, b) = \left[A_s' J_{v_s}(K_s \rho) + B_s' N_{v_s}(K_s \rho) \right] \left[C_s' e^{jv_s \phi} + D_s' e^{-jv_s \phi} \right] \left[E_s' e^{\gamma_s z} + F_s' e^{-\gamma_s z} \right] e^{j\omega t}$$

where

$$\gamma_s = \alpha_s + j \beta_s \quad - \text{propagation constant along the } z \text{ direction}$$

$$K_s = \sqrt{(\gamma_s^2 + \omega^2 \mu_s \epsilon_s) - j\omega \mu_s \sigma_s}$$

v_s - constant arising from the solution of the scalar wave equation by means of the method of separation of variables.

$J_{v_s}(K_s \rho)$, $N_{v_s}(K_s \rho)$ - Bessel functions of the first and second kinds, respectively.

s - an index number identifying a given medium in problems involving several media.

The media within the slow-wave dielectric resonator are assumed to be homogeneous, isotropic, lossless, and charge-free so that, upon assuming the fields to be axially symmetric ($v_s = 0$), application of the boundary conditions at the end walls then simplifies the general solution to the form:

$$H_{zs} = \left[A_s' J_0(K_s \rho) + B_s' N_0(K_s \rho) \right] \sin \beta_s z e^{j\omega t}$$

with

$$\beta = \frac{n\pi}{L}, \quad n = 0, 1, 2, \dots$$

By definition, $E_z = 0$ for the TE modes so that the only field components under these conditions are H_z , H_ρ , and E_ϕ .

The slow-wave property of this device requires that the phase velocity of the waves moving in the z-direction be equal to the electron velocity of the beam to which it is ordinarily coupled. Since the phase velocity along the z-direction, v_p , must equal the electron velocity, v_e , and this latter velocity is always less than the velocity of electromagnetic propagation, c , in the medium in which the beam exists, then the arguments of the Bessel functions in regions I and III will be imaginary numbers. The modified Bessel functions $I_0(\gamma\rho)$ and $K_0(\gamma\rho)$, respectively, are therefore used to describe the fields in these regions. The values for the arguments in the respective regions follow from:

$$K_s = \sqrt{\omega^2 \epsilon_s - \beta_s^2} = \frac{\omega}{c_s} \sqrt{1 - \left(\frac{c_s}{v_p}\right)^2}$$

In region I, the region of the beam, $v_p = v_c < c_o$, but $v_{ps} = \frac{\omega}{\beta_s}$ will be the same in all three regions since $\beta_1 = \beta_2 = \beta_3$ follows from the boundary conditions. Therefore,

$$\begin{aligned} K_1 &= K_3 = j \gamma \\ \gamma &= \frac{\omega}{c_o} \sqrt{\left(\frac{c_o}{v_p}\right)^2 - 1} = \frac{2\pi}{\lambda_o} \sqrt{\left(\frac{c_o}{v_p}\right)^2 - 1} \\ \text{and} \\ K_2 = \Gamma &= \frac{\omega}{c_o} \sqrt{\frac{\epsilon}{\epsilon_o} - \left(\frac{c_o}{v_p}\right)^2} = \frac{2\pi}{\lambda_o} \sqrt{\frac{\epsilon}{\epsilon_o} - \left(\frac{c_o}{v_p}\right)^2}. \end{aligned}$$

For teflon as the dielectric material of the cylinder, $\frac{\epsilon}{\epsilon_o} = 2.08$ and the permissible range of values for the phase velocity, which will cause resonance under the desired conditions, is then

$$0.693 \leq \frac{v_p}{c_o} \leq 1.0.$$

The field expressions from which the total TE_{omn} fields for the slow-wave,

dielectric resonator are derivable, are, then:

$$H_{z1} = A' I_0(\gamma \rho) \sin \beta z e^{j\omega t}$$

$$H_{z2} = [B' J_0(\gamma \rho) + C' N_0(\gamma \rho)] \sin \beta z e^{j\omega t}$$

$$H_{z3} = D' K_0(\gamma \rho) \sin \beta z e^{j\omega t}$$

$$E_{z1} = E_{z2} = E_{z3} = 0.$$

3.2.2.3.3 Design Curves for the TE_{omn} Modes

Having obtained the field expressions for the TE_{omn} modes of the slow-wave dielectric resonator, one then derives the characteristic equation from the boundary conditions at the inner radius, $\rho = a$, and the outer radius, $\rho = b$, of the dielectric cylinder. The characteristic equation for the TE_{omn} modes is found to be:

$$\frac{\frac{p}{q} J_1(q) - \frac{I_1(p)}{I_0(p)} J_0(q)}{\frac{p}{q} N_1(q) - \frac{I_1(p)}{I_0(p)} N_0(q)} = \frac{\frac{w}{v} J_1(v) + \frac{K_1(w)}{K_0(w)} J_0(v)}{\frac{w}{v} N_1(v) + \frac{K_1(w)}{K_0(w)} N_0(v)}$$

where,

$$p = \frac{a}{\lambda_0} 2\pi \sqrt{\left(\frac{c_0}{v_p}\right)^2 - 1} = \frac{a}{b} w$$

$$q = \frac{a}{\lambda_0} 2\pi \sqrt{\frac{\epsilon}{\epsilon_0} - \left(\frac{c_0}{v_p}\right)^2} = \frac{a}{b} v$$

When parametric values are affixed to ϵ/ϵ_0 and v_p/c_0 , the left side of the characteristic equation becomes a function of a/λ_0 alone, $f(a/\lambda_0)$, and the right side a function of b/λ_0 only, $g(b/\lambda_0)$. Technical Progress Report No. 5 (15 June 1957) describes the manner in which these functions are computed and graphed, and how the design curves are then obtained. The design curves, a/λ_0 versus b/λ_0 , for the TE_{omn} modes of the slow-wave,

dielectric resonator appear in Figs. 16, 17, 18, 19, 20, and 21. These curves present the values of the radii a and b which are compatible for resonance in a desired mode, at any frequency.

3.2.2.3.4 The TE_{omn} Mode Charts

The mode charts consist of graphs of b/λ_0 versus b/L . Values for b/λ_0 are necessarily taken from the design curves, and $b/L = (b/\lambda_0) \left(\frac{2 c_0}{n v_p} \right)$ since $L = \frac{n}{2} \frac{v_p}{c_0} \lambda_0$. Identical to the case for the TM_{omn} modes, the parametric values for which modes are plotted are:

$$\epsilon/\epsilon_0 = 2.08$$

$$v_p/c_0 = 0.80, 0.88, 0.93, 0.97, 1.00$$

$$m = 1, 2, 3$$

$$n = 1, 2, 3, 4, 5, 10, 15$$

$$a/b = 0.2, 0.5, 0.8.$$

Plotted to a common scale, the TE_{omn} mode charts are presented in Figs. 22, 23, and 24. The ratio a/b is observed to have a profound effect on the mode separation capability of this device, and it is the existence of this parameter in the slow-wave dielectric resonator which distinguishes it from the conventional cylindrical cavities.

3.2.2.3.5 Complete Mode Representation for the Case of Axially Symmetric Fields in the Slow-Wave Dielectric Resonator

For the special case of only axially symmetrical fields, $v_s = 0$ in the slow-wave dielectric resonator, the hybrid modes not being supported by the structure under this condition. Therefore, the complete mode charts for the slow-wave dielectric cavity will consist of the superposition of the individual TE_{omn} and TM_{omn} charts. Figure 25 is then the complete mode description for the teflon dielectric resonator where $a/b = 0.5$, and Fig. 26 is the complete mode description for $a/b = 0.2$. The mode-separating capability of this device is again apparent when these two graphs are compared.

The improvement in mode separation performance which is afforded by the slow-wave dielectric resonator over cylindrical metal cavities is illustrated by comparing the TM_{omn} modes of Fig. 26 with those for the metal cavity in Fig. 27. Both plots of the TM_{omn} modes are presented on

FIGURE 16 THE CAVITY DIMENSIONS b/λ_0 VERSUS a/λ_0 FOR THE TE_{omn} MODES OF THE DIELECTRIC HARMODOTRON, WHERE $\epsilon/\epsilon_0 = 2.08$ AND $v_p/c = 0.70$. (λ_0 = FREE SPACE WAVELENGTH).

FIGURE 17 THE CAVITY DIMENSIONS b/λ_0 VERSUS a/λ_0 FOR THE TE_{omn} MODES OF THE DIELECTRIC HARMODOTRON, WHERE $\epsilon/\epsilon_0 = 2.08$ AND $v_p/c = 0.80$. (λ_0 = FREE SPACE WAVELENGTH).

FIGURE 18 THE CAVITY DIMENSIONS b/λ_0 VERSUS a/λ_0 FOR THE TE_{omn} MODES OF THE DIELECTRIC HARMODOTRON, WHERE $\epsilon/\epsilon_0 = 2.08$ AND $v_p/c = 0.88$. (λ_0 = FREE SPACE WAVELENGTH).

FIGURE 19 THE CAVITY DIMENSIONS b/λ_0 VERSUS a/λ_0 FOR THE TE_{omn} MODES OF THE DIELECTRIC HARMODOTRON, WHERE $\epsilon/\epsilon_0 = 2.08$ AND $v_p/c = 0.93$. (λ_0 = FREE SPACE WAVELENGTH).

FIGURE 20 THE CAVITY DIMENSIONS b/λ_0 VERSUS a/λ_0 FOR TE_{omn} MODES OF THE DIELECTRIC HARMODOTRON, WHERE $\epsilon/\epsilon_0 = 2.08$ AND $v_p/c = 0.97$. (λ_0 = FREE SPACE WAVELENGTH).

FIGURE 21 THE CAVITY DIMENSIONS b/λ_0 VERSUS a/λ_0 FOR THE TE_{omn} MODES OF THE DIELECTRIC HARMODOTRON, WHERE $\epsilon/\epsilon_0 = 2.08$ AND $v_p/c = 1.00$. (λ_0 = FREE SPACE WAVELENGTH).

FIGURE 22 TE_{omn} MODES FOR $a/b = 0.2$

FIGURE 23 TE_{omn} MODES FOR $a/b = 0.5$

FIGURE 24 TE_{omn} MODES FOR $a/b = 0.8$

FIGURE 25 THE TM_{0mn} AND TE_{0mn} MODES FOR THE SLOW-WAVE DIELECTRIC RESONATOR, WITH $a/b = 0.5$

FIGURE 26 THE TM_{0mn} AND TE_{0mn} MODES FOR THE SLOW-WAVE DIELECTRIC RESONATOR, WITH $a/b = 0.8$

FIGURE 27 TM_{0mn} MODE CHARTS FOR CYLINDRICAL METAL CAVITIES, TOGETHER WITH AN INDICATION OF THE RELATIVE LOCATION OF THE TE_{0mn} MODES.

the same scale for purposes of direct comparison. Figure 27 also includes an indication of the intercepts for the various families of TE_{omn} modes, and thereby serves to indicate the highly complex and crowded mode pattern for the axially symmetric fields of the conventional cavities. The mode separation property of the slow-wave structure, on the other hand, can be enhanced even more as the ratio a/b is increased even further. The limiting value for this ratio is obviously one.

3.2.2,3.6 Field Plots for the TM_{omn} Modes

Output power from the slow-wave dielectric resonator is presently obtained by coupling an output waveguide to the resonator fields through an aperture in an end wall. It is therefore desirable to determine whether or not an optimum location for the output aperture exists, and, if so, how this position is determined.

The answer to these questions lies in the investigation of the resonator fields at the end walls. For the TM_{omn} modes, the expressions for the fields at the end walls become:

$$\begin{aligned} E_{\rho 1} - E_{\rho 2} - E_{\rho 3} &= 0 \\ E_{z1} &= A I_0(\gamma \rho) \cos \omega t \\ E_{z2} &= [B J_0(\Gamma \rho) + C N_0(\Gamma \rho)] \cos \omega t \\ E_{z3} &= D K_0(\gamma \rho) \cos \omega t \\ H_{\phi 1} &= -A \frac{\omega \epsilon_0}{\gamma} I_1(\gamma \rho) \sin \omega t \\ H_{\phi 2} &= \frac{-\omega \epsilon}{\Gamma} [B J_1(\Gamma \rho) + C N_1(\Gamma \rho)] \sin \omega t \\ H_{\phi 3} &= \frac{\omega \epsilon_0}{\gamma} D K_1(\gamma \rho) \sin \omega t. \end{aligned}$$

From the boundary conditions at $\rho = a$ and $\rho = b$, the constants B , C , and D can be normalized with respect to A . The field expressions are then explicitly determined except for the arbitrary amplitude factor A which appears in each of the formulas.

The time independent amplitude distributions for the electric field are plotted in Figs. 28, 29, and 30, where the inner cylinder radius has been fixed at $a/\lambda_0 = 0.4$ and $v_p/c_0 = 0.93$. The outer radius is then permitted to take on values corresponding to the mode numbers $m = 1, 2, 3$,

FIGURE 28 THEORETICAL, TIME INDEPENDENT, RELATIVE FIELD INTENSITY E_z FOR THE TM_{01n} MODES WITH $v_p/c_0 = 0.93$, $a/\lambda_0 = 0.4$, and $z = 0, L$.

FIGURE 29 THEORETICAL, TIME INDEPENDENT, RELATIVE FIELD INTENSITY E_z FOR THE TM_{02n} MODES
 WITH $v_p/c_0 = 0.93$, $a/\lambda_0 = 0.4$, and $z = 0, L$

FIGURE 30 THEORETICAL, TIME INDEPENDENT, RELATIVE FIELD INTENSITY E_z FOR THE TM_{03n} MODES
 WITH $v_p/c_0 = 0.93$, $a/\lambda_0 = 0.4$, and $z = 0, L$

as found in the design curves for the TM_{omn} modes. Similar plots for the magnetic field at the end walls appear in Figs. 31, 32, and 33. These graphs clearly indicate the existence of an optimum location for coupling to an output waveguide, and the necessity for proper positioning of the output aperture if maximum power output is to be achieved. From these field plots one can then locate the output aperture at the most desirable position, depending upon whether the output couples to the electric or the magnetic field of the slow-wave dielectric resonator.

3.2.2.4 Millimeter Experiment

During the past interval, preparations have been made for performing a beam coupling experiment with the slow-wave dielectric harmodotron at a wavelength of 5.18 millimeters. This wavelength corresponds to the twenty-first harmonic of the rebatron frequency used to modulate the beam.

This particular frequency was chosen for two reasons. First, this is the highest frequency presently available from QK295 bench-type signal sources at this laboratory. By means of bench measurements, the microwave properties of the resonator can be determined and optimized with relative ease before being used with the rebatron under vacuum.

Second, the last successful experiment utilizing the slow-wave dielectric harmodotron for coupling to the relativistic electron beam of the rebatron was performed at a wavelength of nine millimeters. It is felt that this step in frequency will be significant in establishing the usefulness of this device at higher and higher frequencies.

The preliminary bench measurements have already been completed, and the rebatron experiment is scheduled to take place in about two weeks.

3.2.2.5 Plans for the Next Interval

Experimental investigation of the slow-wave dielectric resonator will continue, in connection with the experiment described in the preceding section. The analysis of this structure will next involve the investigation of the boundary value problem approached from the most general considerations. This will involve the study of the hybrid modes for this device.

FIGURE 31 THEORETICAL, TIME INDEPENDENT, RELATIVE FIELD INTENSITY H_ϕ FOR THE TM_{01n} MODES WITH $v_p/c_0 = 0.93$, $a/\lambda_0 = 0.4$, AND $z = 0, L$

FIGURE 32 THEORETICAL, TIME INDEPENDENT, RELATIVE FIELD INTENSITY H_ϕ FOR THE TM_{02n} MODES WITH $v_p/c_0 = 0.93$, $a/\lambda_0 = 0.4$, and $z = 0, L$.

FIGURE 33 THEORETICAL, TIME INDEPENDENT, RELATIVE FIELD INTENSITY H_ϕ FOR THE TM_{03n} MODES WITH $v_p/c_0 = 0.93$, $a/\lambda_0 = 0.4$, and $z = 0, L$.

3.3 Detecting and Measuring Techniques

3.3.1 Purpose

The objective of this research is to develop suitable detectors and power and frequency measuring instruments for evaluating the characteristics of the radiation produced by any of the beam coupling schemes and for using the radiation as a diagnostic tool in research.

3.3.2 Millimeter Wave Techniques - A.W. Swago

3.3.2.1 Crystal Multipliers

Several more necked-down, straight-line multipliers for 8 mm drive were electroformed during this interval. These were made with different spacings, in an attempt to emphasize various harmonic numbers. Two were assembled, and were tried with various combinations of E-H plane tuners and dielectric phase shifters of the type described in the last quarterly report. Although complete data were not taken, it was found that, while the desired wide range of frequency insensitivity had been achieved, the efficiency at all points was relatively poor. Use of a commercial 1N53 cartridge as a plug-in multiplier agent gave results approximately comparable with whisker-crystal combinations built directly into the guide.

While these results have been essentially discouraging, there still remain one or two assembly combinations which have not been tried. Tests on these will be carried out before any attempt is made to transfer efforts to entirely different types of multiplier construction. (See 3.3.2.2)

Mandrels were designed, and necked-down guide sections in the RG-99/U guide size have been electroformed. The attempt here will be to multiply from 4 mm fundamental power to 2 and 1 mm by using second, and third, or possibly fourth harmonics. An Amperex type DX151 tube has been ordered for use as the driving source for this multiplier, but delivery is not expected until next quarter. In the interim, a classified tube will be used. If the attempt to miniaturize the 1N53 cartridge is successful, use of these packaged diodes as multiplier elements will be tried.

3.3.2.2 Frequency Multiplier Considerations

In reviewing the efforts expended on crystal multipliers by this group, the question arose as to what might be the limiting efficiency to be reached by non-linear resistive elements. Possible analog circuits

for several multiplier constructions were drawn, and one which could represent essentially two types, including the present straight-line version, was considered in more detail. The analog circuit is sketched in Fig. 34.

FIGURE 34 ANALOG CIRCUIT

In the actual multiplier, power is coupled into the 8 mm structure, which can be tuned so that maximum power can be transferred to the whisker for further transmission to the crystal diode junction. The current flowing through the whisker not only transfers the 8 mm power to the crystal, but harmonics present then radiate into a tunable harmonic structure. In the analog, the two tanks in series represent the 8 mm and harmonic systems as reflected back to the whisker, which then forms a series path with the crystal. In the analog circuit, it was decided to use about 1500 cps as the fundamental frequency, and the tanks were constructed with the highest-Q coils available. A 1N56-A crystal was chosen for maximum current capacity. It was assumed that although the characteristics would not agree with the diodes actually in use, its operation would not be radically different. No bias was used. Only two tests were run with this circuit before the end of this interval, one with the tanks tuned to precisely the fundamental and second harmonic frequencies, the other with the harmonic tank tuned to give the best harmonic voltage waveform as viewed on an oscilloscope. The results were not significantly different in the two cases, with the second harmonic power being about 13 db below the fundamental.

It is planned to again check this analog circuit to study the effects on conversion efficiency obtained by varying the effective shunt resistance

of the tanks, and by using bias.

When the tank was tuned to a higher harmonic, the fifth through the eighth, for example, it was found that the resistive effect of the crystal during the half cycle of fundamental conduction so lowered the Q of the harmonic tank as to prevent oscillation at the harmonic frequency during that half cycle. However, the 13 db figure obtained suggests that with crystal multipliers, the 10 db conversion efficiency sometimes obtained by other groups under optimum conditions may be approaching a practical limit with the multiplier configurations presently used.

If a mathematical analysis of the analog circuit shown in Fig. 34 is attempted under periodic boundary conditions, the system determinant yields a fourth degree polynomial. Based on experience, and assuming oscillatory conditions, the types of roots may be guessed, so that roots may be extracted. These become so involved with respect to any particular parameter, however, that effects of its variation cannot be clearly seen. Hence, this approach was abandoned.

In other high-order multiplying systems, for example, harmonic cavities driven by rebatron beams, the overall energy will also vary exponentially. Since this represents an amplitude variation, with presence of a discrete band of frequencies, the signal extractable at a given "harmonic frequency" may not necessarily be directly related to the power actually delivered at this frequency, and may differ with expected values obtained from Fourier series analysis.

The possibility of checking various analog configurations, followed by attempts to synthesize microwave equivalents, may well point to ways of improving conversion efficiency. If, in addition, the non-linearity of the crystal element is included, however, the problem becomes one of non-linear mechanics, and the mathematical processes of handling the problem may become extremely cumbersome.

For the several reasons above, therefore, the advisability of carrying out an overall study of multiplier circuits using an electronic analog computer, recently obtained by the Electrical Engineering Department, is being considered at the present time. The results obtainable from such a study will be judged against time required for programming as well as actual computation time before a firm decision to proceed is made.

3.3.2.3 Other Components for 1 and 2 mm Wavelengths

During this interval, tapered transition sections were made for junctions between RG-96/U and RG-99/U guide sizes to the "1 mm" guide (0.049 inch $\times$ 0.022 inch I.D.) adopted in this laboratory. This completes the group contemplated, so that transitions are now available from 8 mm to 4, 2, and 1 mm, and from 4 mm to 2 and 1 mm.

A tunable shorting plunger for the 1 mm guide, using differential screw action for slow tuning and spring loading to prevent backlash, has been designed and constructed. Minimum size and weight were also made a principle design factor. Since this element has not yet been properly tested, further details will be withheld until the end of the next interval.

3.3.3 Bolometers, and Crystal Detectors - J. Stafford

In this past quarter, the design and construction of suitable detectors for 1, 2, and 4 mm wavelengths and associated equipment has been continued. The main areas of effort have been centered on construction of:

- a. Bolometer mounts
- b. Crystal mounts
- c. Coherent circuits.

3.3.3.1 Bolometer Mounts

In order to obtain a reasonably accurate indication of microwave power, a device with a square law response is to be sought. It is believed that the bolometer is among the devices which more nearly approximate this requirement for a given range of incident power. In addition, since the temperature sensitive wire has a response which is proportional to the heat capacity of the wire, the sensitivity is proportional to the volume or mass of the wire.

$$\frac{1}{r_T} \frac{\partial^2 T}{\partial z^2} + (g - \alpha) = c_v \rho \Delta V \frac{\partial T}{\partial t}$$

where

- r_T = thermal resistivity
- T = temperature (absolute)
- z = coordinate along which wire lies
- g = power dissipated

α = power reradiated
 c_v = specific heat capacity
 ρ = density of wire
 ΔV = volume of wire
 t = time.

Consequently, it appears feasible that for a small (~ 16 μ inch) wire, the sensitivity could very well exceed that of a crystal detector.

Also, one is always questioning the degree of sensitivity of a crystal. No absolute method has been determined to evaluate the relative sensitivities of two identical crystals, other than a substitution method. In the case of a bolometer, however, the sensitivity should remain the same from one element to the other, providing there is continuity through the element.

Originally, work began using 50 μ inch Wollaston wire already on hand. The two biggest problems quite naturally are (a) building a suitable mount, and (b) etching away the silver jacket without breaking the remaining platinum core.

A series of three mounts have been built and tried. The first (Fig. 35) is essentially an in-guide construction where the wire is secured on one of the wide guide walls. It is then passed through the other wall, being insulated with a glass sleeve, then through a teflon block, and finally it is fastened to the center conductor of a BNC panel connector. These pieces are then bolted to a brass block as shown. This type of mount proved to be inadequate because of the inability to conveniently etch the wire without breaking it.

A second mount, of a wafer type rather than an in-guide type of construction, was then used (see Fig. 36). This is similar to the commercially available mounts for 4 and 8 mm bolometers. The wire was etched using a micro-manipulator, carrying drops of acid on a glass rod. Using this method, a 50 μ inch bolometer was built and tested. When compared with a commercial bolometer, the relative sensitivity was found to be ~ -15 db. When compared with a 1N53 crystal known to be quite sensitive, the relative sensitivity was found to be ~ -14 db. This bolometer had a cold resistance of ~ 100 ohms as compared to the commercial

FIGURE 35 SCHEMATIC OF FIRST BOLOMETER MOUNT USED.
(Although rigidity is attained here, cumbersome etching procedures caused this mount to be discarded.)

FIGURE 36 FLEXIBLE MICA MOUNT SIMILAR TO COMMERCIAL BOLOMETERS
(This mount is adequate for larger wires but was found to be too pliable for use with small wires (16 μ inch.)

bolometer's resistance of 200 ohms. A ratio of 2:1 in resistance indicates a ratio of diameters to be .707:1 or indicates that the commercial bolometer has a wire diameter of $\sim 34 \mu$ inches and should be expected to have a greater sensitivity.

In the above measurements the experimental bolometer gave an indication under matched (E-H plane tuner) conditions of 4 db over noise. An interesting feature of this test was the apparently greater sensitivity of a bolometer when compared with the crystal. When this construction was attempted using a 16μ inch wire, it was found that the pliability of the mica sheet considerably reduced the life of a wire, if not rendering its construction impossible.

The third mount is of a construction similar to the block and wafer used at the Bell Telephone Laboratories for testing crystals. (Fig. 37.) The wire is passed through the teflon wafer, and through the waveguide insert as with the first mount, and fixed to both the bottom of the waveguide and the termination pin with silver paint. Thus far, no 16μ inch bolometer has been constructed because of one fault or another with the etching technique. The most serious problem has been the violent reaction between the copper waveguide and the etching acid, breaking the fine wire before it is completely etched. The gold plating will not withstand the presence of the acid for a duration of even 30 seconds, the approximate time required to dissolve the silver jacket.

It is believed that this holder is the most desirable of the three since it combines both the in-guide and wafer types of construction, thereby utilizing the properties of rigid construction along with an expendable, easily replaced unit.

Figure 38 is a picture of the stand used in etching the thin wires. The wafer is clamped into the vise over the center hole. Acid is then forced up through the hole. This action can be viewed using a 150 power microscope.

3.3.3.2 Crystal Mounts.

With a view to providing a more compact crystal detector than the previously used detectors requiring a differential screw drive, an effort was made to reduce a 1N53 cartridge by a factor of two or three. Not all dimensions have been reduced by this factor because of the limitation of machine shop capabilities. Crystal dicings already on hand were prepared

FIGURE 37 THIRD TYPE OF MOUNT SIMILAR TO THE ONE USED AT BELL TELEPHONE LABORATORIES. (Rigidity and easy accessibility for etching make this mount the most desirable.)

FIGURE 38 STAND USED IN ETCHING THIN WIRES

Stand in center foreground is one used for etching bolometers. Also shown is stand used to adjust the height of the acid, and the 150 power microscope used to view etching. Sufficient light is carried through column of acid.

FIGURE 39 FINAL ASSEMBLY JIG

Jig used in final assembly of miniature crystal cartridges is shown in center foreground; also shown is assembly lathe and source for 60 cycle sweep voltage. Note crystal in assembly jig.

and more were ordered.

The three biggest problems involved were (a) jigging and assembly, (b) suitably preparing the whisker (tungsten), and (c) seating the whisker permanently into the crystal.

Jigging was facilitated by procuring a tailstock and collets for a jeweler's lathe. The headstock and bed were found among some discarded machinery. A final assembly jig (Fig. 39) was made by Mr. Lowe in the machine shop.

At first, an attempt to solder the tungsten whisker to the brass post was made. This method was both messy and tedious. Finally the whisker was spot-welded onto the side of the post instead of on the top, as is usually done. The insulating bead is then pushed onto the post and the whisker is formed and pointed.

The final assembly is completed by driving the crystal into the pointed whisker while sweeping the unit with a 60 cycle voltage. Upon attaining a suitable contact, i.e., where the forward transmission is suitably steep, the contact is made firm by imparting a solid blow to the jig. The mechanism of this action is not completely understood, but the results indicate an improvement. A comparison with a 1N53 cartridge when both are being swept at a 60 cycle rate is seen in Fig. 40. This new cartridge using 1N26 material has been inserted into a suitable waveguide mount and tested at 5 mm. The overall sensitivity is approximately one-fourth that of a 1N53 crystal inserted in the same circuit.

It is expected that a more sensitive crystal can be built using 1N53 material, preparing the surface more carefully, and taking greater pains while preparing the whisker point. Also, the final assembly jig will be modified so that the assembly can take place with 5 mm power incident on the cartridge.

3.3.3.3 Coherent Circuit

A coherent detector using switching techniques has been designed and is in the process of being built. This circuit originated at the Stanford Research Institute and was reported to be capable of detecting signals 30 to 40 db below the noise level. The circuit was modified so as to be more adaptable to our specific needs. It is expected that this circuit will be finished and tested in the following quarter.

FIGURE 40. 60 CYCLE CHARACTERISTIC OF MINIATURE CRYSTAL CARTRIDGE USING 1N26 MATERIAL (TOP) AND SIMILAR CURVE, TO SAME SCALE, FOR 1N53 CRYSTAL (BOTTOM)

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