AXIALLY EXTENDED INTERACTION AREA
INVERTED COAXIAL MAGNETRON

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The report summarizes the results of a twelve month feasibility study beginning February 1962 and ending February 1963. The work was performed under the general direction of J. Drexler, Director of Engineering at S-F-D laboratories, Inc.

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ABSTRACT

This report describes the areas of endeavor and results obtained on a twelve month feasibility effort directed toward high power generation at millimeter wave frequencies. Axially extended interaction in an ICEM coaxial magnetron was the means employed toward attaining this goal. The work described in this report was performed at 35 Gc.

The ICEM coaxial magnetron, which is an extension of the CEM coaxial magnetron principle, increases the number of resonators possible and hence the power generation capabilities of the CEM coaxial magnetron. The axially extended interaction approach to high power generation further increases the power generation capabilities by increasing the number of resonators by a factor of two or more.

The mode control problems associated with the TE_{011} mode cavity used in a single stage ICEM coaxial magnetron had already been solved. However, in a two stage tube employing two sets of vane resonators, a method of mode selection was required which would allow one to operate in a particular TE_{01n} mode and yet inhibit operation in the TE_{01(n+1)} mode of a particular cavity. Several special hybrid test vehicles were employed to study this problem.

Four two stage ICEM coaxial magnetrons were constructed and evaluated. The two sets of vane resonator assemblies of this tube were successfully phase locked through the common cavity to which each is coupled. The output waveguide is coupled to this common cavity. A peak power output of over 150 kw at 35 Gc has been demonstrated.

The feasibility of the axially extended interaction ICEM coaxial magnetron has been demonstrated. The extension of this principle to high frequencies opens the possibility of generating high peak powers at approximately three times the frequency employed in this study.
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1.0 AN INTRODUCTION TO THE CEM® AND ICIM® COAXIAL MAGNETRONS

The difficulty encountered in present-day rising-sun Ka-band magnetrons can be traced directly to their small internal structure. All of the conventional tubes utilize a rising-sun anode containing 17 to 22 resonators. The small number of resonators results in a correspondingly small cathode diameter. The high cathode current loading and the high power density of this fine-grained structure limit the available power, life and reliability. Although it would be desirable to increase the number of resonators and size of cathode in order to reduce the demands on the structure, numbers of resonators above 22 show very small separation between the desired and undesired modes. The problem has been solved in the CEM and ICIM coaxial magnetrons through the use of the TE_{011} mode cavity. Since the principles of operation of the CEM and ICIM structures are identical and since the CEM coaxial magnetron is similar to the conventional magnetron, only the CEM coaxial magnetron principles of operation will be discussed here.

The CEM coaxial magnetron has an array of vane resonators in which alternate resonators are coupled to the TE_{011} mode of a coaxial cavity through coupling slots in the shell of the inner cylinder. Since the currents in the TE_{011} mode have the same phase at all points along the circumference of the cavity wall, all the coupling slots are driven in phase and, therefore, all the coupled vane resonators are excited in phase. Figure 1 shows the anode structure and field configuration.

The uncoupled resonators which are adjacent to the coupled resonators, are excited by the RF magnetic field threading a pair of coupled and uncoupled resonators. This RF magnetic field is in opposite directions in adjacent resonators and the electric fields across the vane tips of adjacent vanes are opposite in direction and thus out of phase by 180° or π radians. This field configuration, therefore, is known as a σ mode.
Figure 1: Anode structure of the CEM coaxial magnetron.
The CEM structure exhibits excellent frequency stability as evidenced by the pulling and pushing figures obtainable. Also in one X-band tube, the $Q_u$ is about 7000 as compared to 800 for a conventional strapped magnetron. The high $Q_u$ allows higher $Q_e$'s to be employed, resulting in higher circuit efficiency and, therefore, greater overall efficiency.

Advantage is also taken in this design of the fact that conventional magnetrons operate at too high an electronic impedance level for maximum electronic efficiency. This means that the RF electric field strength is too great. To lower the RF electric fields, one would need to reduce $Q_e$. However, this cannot be effected since the pulling figure would be raised to an intolerable value. In the CEM and ICEM structures, the frequency stabilizing cavity makes possible steady state operation at the optimum impedance level.

A more detailed explanation of the CEM coaxial magnetron can be found in an article by J. Feinstein and R. J. Collier, "A Magnetron controlled by a Symmetrically Coupled TE$_{011}$ Mode Cavity," LeVide, No. 70, July-August 1957.

The ICEM coaxial magnetron is an extension of the CEM principles applied to an inverted magnetron structure. Figure 2 illustrates the basic configuration of a tunable ICEM coaxial magnetron.

The mode selecting cavity consists of a hollow cylinder closed at one end by a disk which is a combination tuning plunger and coupling plate. The disk is supported by a coaxial rod which converts the hollow cavity to a coaxial cavity. This TE$_{011}$ mode coaxial cavity is coupled to alternate vane resonators through long narrow axial slots in the cylinder wall. The cathode is an annular ring which encloses the vane resonator system. Th. TE$_{011}$ mode cavity is coupled to a circular TE$_{01}$ mode waveguide around the periphery of the disk tuning plunger. The cathode is insulated from the body by means of internal ceramic insulators. The tuning rod is guided by two sapphire bearings.
FIGURE 2  CROSS-SECTION OF TUNABLE ICRM COAXIAL MAGNETRON
The inverted structure has several advantages over the CEM coaxial magnetron structure. The number of resonators is about four times greater, yielding higher power capabilities; the cathode area is about six times greater, yielding lower current density requirements; and the output couples to TE_{01} mode circular waveguide which has almost ten times the power handling capabilities of dominant mode rectangular waveguide. Figure 3 compares the interaction area of the ICEM coaxial magnetron to that of a conventional rising-sun magnetron structure.

The present status of the single-stage Ka-band ICEM coaxial magnetron will be stated briefly. In March 1962, a tube generated a peak power of 293 kW with an average power of 49 watts and a pulse length of 0.56 μsec. This is approximately three times higher than has been reported for any Ka-band tube at this pulse length. In addition, several tubes exhibited efficiencies approaching 30% which permitted the generation of up to 180 kW peak and 97 watts average power at 0.5 μsec pulse length. A tunable Ka-band model generated a minimum peak power output of 150 kW at 0.5 μsec pulse length over a 2.3 Gc band.

Several tubes were made for evaluation by the Air Force Cambridge Weather Research Group. These tubes were evaluated in the AN/TPQ-11 Cloud Analysis Radar over the past fifteen months. The first tube failed after 917 hours of operation. The second tube operated for 1418 hours at which time the complete system was removed from service. The third tube is still operating with over 5000 hours to date. This radar system is designed to radiate 100 kW peak power and 50 watts average power output at a pulse length of 0.5 μsec.
FIGURE 3 A COMPARISON OF A 32 VANE RISING-SUN STRUCTURE AND A 120 VANE ICMH STRUCTURE
2.0 INTRODUCTION TO THE EXTENDED INTERACTION ICEM COAXIAL MAGNETRON

The main cavity resonator presently used in the single-stage ICEM coaxial magnetron is one half-wavelength long and operates in the TE_{011} mode. A cavity resonator could also be built which would operate in the TE_{012} mode and would, therefore, be a full wavelength long. One could conceive of using two resonator arrays, one coupled to the upper half and one coupled to the lower half of this TE_{012} mode cavity resonator. It turns out that there is insufficient room for the magnetic pole pieces if such a scheme were used and it is, therefore, necessary to use a longer cavity. A TE_{014} mode cavity would permit sufficient room for two sets of vane resonator arrays. This two-section ICEM coaxial magnetron would be capable of generating nearly twice the power output of the present ICEM structure.

The two major difficulties which might be anticipated in the development of such a device are its physical complexity and the possibility of operation in an undesired mode of the TE_{0ln} family. This is not a problem in the present single-stage design. In order to simplify the mechanical assembly operations, one plan could be to construct modular units which could be heliarc welded together. An approach to inhibiting the higher and lower order TE_{01} modes would be to use a number of mode absorbers located at particular points along the axial length of the cavity.

Figure 1 shows a cross-section drawing of one possible design for a two-stage ICEM coaxial magnetron. The coaxial cavity in this case is designed to resonate in the TE_{014} mode. Two sets of vane resonators are coupled to this coaxial cavity through long narrow coupling slots as in the case of the single-stage tube. The output coupling circuit is also similar to that of the single-stage tube. The two cathodes could be operated together using a single input stem or could be operated independently which would require a second input stem. Note the modular construction illustrated by the three groups of paired lip flanges which are heliarc'd to form vacuum seals.
FIGURE 4  CROSS-SECTION OF TWO-STAGE Icem COAXIAL MAGNETRON
We might consider why axial extension of the interaction area appears to be more desirable than circumferential extension. It is conceivable that an ICEM coaxial magnetron could be designed to operate in the $\text{TE}_{021}$ or $\text{TE}_{0m1}$ mode and would have $m$ times as many resonators as in the case of the $\text{TE}_{011}$ mode ICEM structure. This, of course, would result in considerably larger interaction areas, but would present some inherent problems which would be difficult to solve. First, it is difficult to devise ways of inhibiting an undesired $\text{TE}_{0,m+1,1}$ mode without affecting a desired $\text{TE}_{0,m,1}$ mode. Second, a mundane but serious difficulty arises with regard to the thermal coefficient of expansion. As the anode shell heats during operation, it expands radially reducing the cathode-anode spacing. If for example a $\text{TF}_{34}$ mode were used, the cavity diameter would be so large that the cathode-anode spacing might be reduced from cold to hot by 25% to 35% resulting in a change of performance with average power. Last, precise large diameter parts become very expensive, particularly the cathode and vane resonator systems.

Another way of increasing the interaction area of a crossed-field oscillator is to increase the axial height of the anode vane resonators. There are two disadvantages to this approach, particularly at millimeter wavelengths. As the height of the vane resonator approaches a half wavelength, the RF fields along the structure become non-uniform as a result of the sine wave variation of fields in the cavity. This effect will lower the electronic efficiency and thereby the overall efficiency of the tube. Further, as the height of the interaction gap increases, the fringing magnetic field and leakage fields increase and the weight of the magnets increases rapidly.
3.0 ELECTRICAL DESIGN CONSIDERATIONS

3.1 Introduction

Two major design areas are immediately apparent when a two-stage device is considered. One is the physical complexity of the device and the second is the suppression of the unwanted $TE_{01n}$ modes.

In the mechanical assembly, the idea of a module unit approach was considered. However, when a series magnetic gap arrangement was selected in preference to the parallel gap arrangement, the number of heliarc welds was reduced. Furthermore, engineering changes could be incorporated in an expeditious manner by virtue of the end cover heliarc welds.

By selecting the shortest length cavity capable of supporting two sets of vane resonators, within physical limitations, the number of modes in the system is minimized. An advantage which occurs simultaneously is that with fewer modes, the frequency separation between the modes is generally greater.

3.2 Design Problems Encountered in the Two-stage Device

In order to minimize the difficulties from undesired $TE_{01n}$ modes, the electrical length of the cavity should be selected to operate at the desired frequency in the $TE_{01n}$ mode having the smallest "n". Figure 5 shows a parallel and series magnetic pole piece gap scheme. The smallest possible "n" that could be used in a parallel magnetic gap arrangement would be 7. The reason for this length is that the center pole piece extension must have twice the cross-section of the end pole piece extensions since it must carry twice the flux of either of the end pole piece extensions. However, when the series magnetic gap arrangement is employed, there is no need for the large cross-section between the gaps since no magnetic flux is being supplied at this point. With just a field shaping intergap pole piece, the length required is significantly reduced. Where the parallel gap arrangement results in a $TE_{017}$ mode cavity, the series gap arrangement results in a $TE_{014}$ mode cavity.
FIGURE 5  COMPARISON OF PARALLEL AND SERIES FEED MAGNETIC CIRCUIT
The mode separation of the $\text{TE}_{01n}$ modes in a $\text{TE}_{014}$ mode cavity is considerably greater than in a $\text{TE}_{017}$ mode cavity. Figure 6 shows the proximity of the $\text{TE}_{013}$ and $\text{TE}_{015}$ modes in a cavity selected for $\text{TE}_{014}$ mode operation. The equation (Ref. 1) for plotting a theoretical mode chart is

$$(fD)^2 = A + Bn^2(D/L)^2$$

where
\begin{align*}
  f & \text{ frequency in megacycles} \\
  D & \text{ diameter of cavity in inches} \\
  L & \text{ length of cavity in inches} \\
  n & \text{ mode number} \\
  B & = 0.348 \times 10^8 \\
  A & = 2.07 \times 10^8 \text{ for } \text{TE}_{01} \text{ family}
\end{align*}

A sample calculation might be helpful at this point:

1. In a full wavelength $\text{TE}_{012}$ cavity where $(D/L) = 1.165$, the frequencies of the desired and adjacent $\text{TE}_{01n}$ modes, when substituting in the above equation, are for
   \begin{align*}
   n = 1 & \quad f = 29.7 \text{ Gc} \\
   n = 2 & \quad f = 35.0 \text{ Gc} \\
   n = 3 & \quad f = 44.1 \text{ Gc}
   \end{align*}

2. In a two wavelength $\text{TE}_{014}$ cavity where $(D/L) = 0.598$, the frequencies of the desired and adjacent modes are for
   \begin{align*}
   n = 3 & \quad f = 31.2 \text{ Gc} \\
   n = 4 & \quad f = 35.0 \text{ Gc} \\
   n = 5 & \quad f = 39.8 \text{ Gc}
   \end{align*}

3. In a three and one half wavelength $\text{TE}_{017}$ cavity where $(D/L) = 0.335$, the frequencies of the undesired and adjacent modes are for

FIGURE 6 CHART SHOWING PROXIMITY OF \( TE_{01n} \) NODES FOR CAVITIES DESIGNED TO BE 1, 2 AND 4 ELECTRICAL HALF-WAVELENGTHS LONG AT 35 Gc
The above examples do not take into account the field perturbations caused by the vane resonators or the output coupling aperture.

In the hybrid tube which is a single resonator array structure coupled to a multi-half-wavelength cavity, the competing $T_{E0}$ modes are sufficiently displaced so as not to cause any difficulty. However in the two-stage device, these competing modes become much closer as discussed earlier. A proposed method of eliminating these modes consists of placing metallic disks at half-wavelength intervals along the length of the cavity. This would divide the longer cavity into several half-wavelength cavities and would insure operation in the desired mode. These disks, called stabilizing disks, would however introduce additional loss in the system and the resultant value of $Q_u$ would decrease.

The $T_{E_{mn}}$ modes of the non-$T_{E0}$ type have longitudinal wall currents while the $T_{E0}$ modes have only circumferential wall currents (of course, all $T_{E_{mn}}$ modes have longitudinal wall currents). Hence, if a narrow circumferential slot were cut in the cavity wall between the two vane resonant structures, it would intercept non-$T_{E0}$ mode currents but not $T_{E0}$ mode currents. In addition, if behind this circumferential slot suitable absorbing material were placed, all the non-$T_{E0}$ mode $Q_u$'s would be reduced.

3.3 The Hybrid Tube Test Vehicle

In the conventional single-stage ICM coaxial magnetron, a single set of vane resonators is coupled to a circular cavity one electrical half-wavelength long. In the proposed two-stage ICM coaxial magnetron, two sets of resonators are coupled to a circular cavity which is four electrical half-wavelengths long. It would have been preferable to use a cavity half as long, but magnetic circuit considerations made this impractical. From considerations of symmetry, it can be assumed...
that in a two-stage device each vane resonator system is coupled to a cavity which is two electrical half-wavelengths long. Therefore, the energy stored in the cavity is approximately twice that of the conventional single-stage ICEM coaxial magnetron.

Upon selection of the TE_{01n} mode cavity for the two-stage ICEM structure, a logical first step was to evaluate a single-stage ICEM tube operating in the TE_{012} mode. This would permit a study of the effect of the higher energy storage ratio (vane to cavity) without the complexity of a double resonator structure.

One of the basic problems associated with both the hybrid tube and the initial two-stage tube is the axial mode control problem. In a conventional ICEM coaxial magnetron, the cylindrical cavity used to control the operating frequency (35 Gc) of the tube is only one half-wavelength long (TE_{011} mode). The closest TE_{01n} mode frequency corresponds to the TE_{012} mode which is 19.6 Gc above the TE_{011} mode frequency. This is shown in the mode chart of Figure 6 by the intersection of the vertical line marked TE_{011} cavity with the mode lines for the TE_{011} and TE_{012} modes. The TE_{012} mode does not cause difficulty in the conventional ICEM coaxial magnetron because its operating frequency is 19.6 Gc away from the resonant frequency of the anode vane resonators.

How close a competing TE_{01n} mode can be to a desired TE_{01n} mode has not yet been determined. However, it can be seen from Figure 6 that as additional half-wavelength sections are added to the cavity the interfering TE_{01n} modes become closer in frequency to the desired TE_{01n} mode. The vertical line marked TE_{012} cavity represents a cavity two electrical half-wavelengths long at 35 Gc. It can be seen that the competing TE_{01n} modes, namely the TE_{011} and the TE_{013} modes are only 6.9 Gc and 9.2 Gc away respectively. If we carry this analysis one step further and look at the vertical line marked TE_{014} cavity, which corresponds to a cavity designed to operate in the TE_{014} mode at 35 Gc, we can see that the
competing \( \text{TE}_{0\ln} \) modes, namely the \( \text{TE}_{013} \) and \( \text{TE}_{015} \) modes, are 3.8 Gc and 4.4 Gc away respectively. The hybrid tube test vehicle could then answer another important question. Can an ICEM coaxial magnetron with a cavity longer than one half-wavelength operate at the desired \( \text{TE}_{0\ln} \) mode frequency when a competing \( \text{TE}_{0\ln} \) mode frequency is only 6.9 Gc away? This, in fact, has been proven possible as described in Section 5.1, Operating Tests and Evaluations - Hybrid Tubes.
4.0 NON-OPERATING TESTS AND EVALUATIONS

4.1 The Hybrid Test Vehicles

A single-stage tunable TE$_{012}$ mode cold tester was designed and built to measure the $Q_u$'s of the TE$_{012}$ mode and to identify other modes of the system. The modes of a cylindrical cavity can be identified by the following characteristics:

1. their tuning rate relative to the theoretical tuning rate and the tuning rates of other modes
2. their ability to excite the anode vane resonators
3. their measured frequency in comparison to the frequencies of known modes
4. through methods of excitation
5. through determination of $Q_u$ reduction as a function of absorber location.

The cold test vehicle was lightly coupled to a rectangular waveguide by means of a single coupling hole located on one end plate of the cavity as shown in Figure 7. Light coupling was employed to avoid field perturbations of the cavity modes. TE$_{012}$ mode $Q_u$'s in the order of 2000 to 2500 were measured. None of the other measurable modes had a $Q_u$ greater than 500. Figure 8 is a theoretical mode chart for a cavity designed to operate in the TE$_{012}$ mode at 35 Gc. The effect of the vane resonators and coupling slots is not included in the mode chart calculations.

Another tunable TE$_{012}$ mode cold test vehicle was built which would symmetrically couple to a circular waveguide output similar to that used in the ICEM coaxial magnetron. That is to say, it used a disk, smaller in diameter than the cavity diameter, which was supported from the opposite end of the cavity by a thin rod. In this way, tunability is incorporated as well as heavy external loading of all modes possessing longitudinal wall currents (all non-TE$_{01n}$ modes). The TE$_{012}$ mode of this cavity could be optimized to yield $Q_u$'s of 3000 to 4000 with TE$_{01}$ mode excitation. No other modes were observed in the frequency range of interest using this method of output coupling.
FIGURE 7  CROSS-SECTION OF TE\textsubscript{012} CAVITY COLD TESTER
FIGURE 8 TE_{012} C_{f}\textsuperscript{2}
Theoretical modes

Actual modes

CAVITY MODE CHART
A hybrid tube cold test vehicle was then constructed to determine the relative values of $Q_u$ for the various $T_{0\text{ln}}$ modes. It was similar to the ICEM coaxial magnetron except for the cavity which was two half-wavelengths long instead of one half-wavelength. The $Q_u$ of the desired or $T_{012}$ mode for this tube was 4350 which is about twice that of a conventional ICEM coaxial magnetron. This is to be expected since the cavity is two half-wavelengths long and, therefore, stores approximately twice the amount of energy. The $T_{013}$ mode of the hybrid tube could not be found because the klystron used was limited to a 40 Ge upper frequency and the theoretical frequency of the $T_{013}$ mode is 44.2 Ge. However, the $T_{011}$ mode was found and the $Q_u$ measured was only 1000, which is low for an ICEM coaxial magnetron.

The low $Q_u$ of the $T_{011}$ mode was attributed to

(a) the relationship of the vane resonator frequency to the cavity frequency, and

(b) the position of the vane resonators with respect to the cavity wall current maximum.

If the vane resonator frequency is the same as or near the cavity frequency, the open circuit at the tips of the vanes is transformed to a short at the back of the resonator. This short, being the lowest impedance point on the cavity wall, should have associated with it the maximum current density point. However, if the cavity frequency is different from the vane resonator frequency (i.e., $T_{011}$ or $T_{013}$ mode operation in a cavity designed to operate in the $T_{012}$ mode), the vane resonators no longer look like a short circuit at the cavity wall and the current maximum occurring at the back of the resonators no longer corresponds to the maximum current point on the inner wall of the cavity. Consequently, both the vane resonator position and length are very poor for both the $T_{011}$ and $T_{013}$ modes. A sketch of the cross-section of a $T_{0\text{ln}}$ mode cavity along with the axial current distribution for the $T_{011}$, $T_{012}$ and $T_{013}$ modes is shown in Figure 9.
Figure 9: Cross-section of a $TE_{01n}$ mode cavity showing the axial current distribution for the $TE_{011}$, $TE_{012}$ and $TE_{013}$ modes.
In the hybrid tube, the competing TE\textsubscript{0ln} modes are sufficiently displaced so as not to cause any difficulty. However in the two-stage device, these competing modes become much closer as discussed earlier. A proposed method of eliminating these modes consisted of placing metallic disks at half-wavelength intervals along the length of the cavity. This divided the longer cavity into several half-wavelength cavities and insured operation in the desired mode. These disks, called stabilizing disks, would however introduce additional loss in the system and the resultant value of $Q_u$ would decrease.

A hybrid tube anode utilizing a stabilizing disk in the cavity was constructed and cold tested to study the effects of this disk since it may be desirable to use this technique in a two-stage tube because of the smaller frequency separation of the adjacent TE\textsubscript{0ln} modes. A photograph of a tuning plunger with the output coupling disk and the stabilizing disk is shown in Figure 10. The values of $Q_u$ obtained at 34.5 Gc when using a stabilizing disk were 269 as compared to 4350 without the stabilizing disk. To insure proper operation of a two-stage tube, it may be necessary to trade $Q_u$ for better mode stability.

4.2 The Two-stage Test Vehicles

A tunable TE\textsubscript{014} cold tester having two arrays of vane resonator structures and coupled to a rectangular waveguide was designed and built. This cold tester is shown in cross-section in Figure 11. The device exhibited $Q_u$'s in the order of 5600 to 7000 for the TE\textsubscript{014} mode. The tunable feature, as in the TE\textsubscript{012} cold tester, made possible the identification of many of the modes which exist in a cavity of this design. A chart is presented in Figure 12 which shows the theoretical and experimentally determined frequencies of some of the modes of this cavity.

The TE\textsubscript{0mn} modes of the non-TE\textsubscript{0ln} type have longitudinal wall currents while the TE\textsubscript{0ln} modes have only circumferential wall currents (of course, all TE\textsubscript{0mn} modes have longitudinal wall currents). Hence, if
FIGURE 10 PHOTOGRAPH OF A TUNING PLUNGER SHOWING THE OUTPUT COUPLING DISK AND THE STABILIZING DISK
FIGURE 11 CROSS-SECTION OF TE₀₁₄ CAVITY COLD TESTER
FIGURE 12 TE_{014} CAVITY
(D/L)^2 = 0.339 \quad L = 0.960'' \quad D = 0.570''

(TE modes only)

--- Theoretical modes
--- Actual modes

TY MODE CHART
a narrow circumferential slot were cut in the cavity wall between the two vane resonant structures, it would intercept non-TE\textsubscript{0ln} mode currents but not TE\textsubscript{0ln} mode currents. In addition, if behind this circumferential slot suitable absorbing material were placed, all the non-TE\textsubscript{0ln} mode \(Q_u\)'s would be reduced. This was done and although the \(Q_u\)'s of the desired mode were not measurably affected, the non-TE\textsubscript{0ln} modes had \(Q_u\)'s too small to measure.

The suppression of the TE\textsubscript{0ln+1} and TE\textsubscript{0ln-1} modes is considerably more difficult to achieve because any of the absorption techniques that could be employed also affect the TE\textsubscript{014} desired mode. Metal disks, judiciously placed along the axis of the cavity, would present the necessary boundary conditions to insure desired mode operation only. This approach has been investigated and yielded the desired result.

A cold test vehicle having two sets of vane resonator structures coupled to a cavity designed to resonate in the TE\textsubscript{014} mode at 35 Gc has been used to evaluate the mode suppression techniques. Since the single-stage TE\textsubscript{012} mode tube (to be discussed later) operated satisfactorily with no tendencies toward operation in the TE\textsubscript{011} or TE\textsubscript{013} modes, it is apparent that a stabilizing disk is not required if the frequency of the interfering TE\textsubscript{0ln} mode is sufficiently removed from the operating frequency of the desired TE\textsubscript{0ln} mode. However in a TE\textsubscript{014} mode cavity, the TE\textsubscript{013} and TE\textsubscript{015} modes, considered interfering modes, are much closer to the desired TE\textsubscript{014} mode frequency than is the case for the shorter cavity length used in the TE\textsubscript{012} mode tube. Figure 13 shows a cross-section of the TE\textsubscript{014} mode cavity used. Also shown are the wall currents for the TE\textsubscript{013} and TE\textsubscript{014} modes.

The measured values of the frequency of the TE\textsubscript{013}, TE\textsubscript{014}, and TE\textsubscript{015} modes along with measured values of \(Q_u\) are as follows:
FIGURE 13 CROSS-SECTION OF TWO-STAGE AMODE SHOWING AXIAL CURRENT DISTRIBUTION FOR THE $TE_{013}$ AND $TE_{014}$ MODES.
The above values were measured by keeping the cavity length fixed with the TE_{014} mode at 34.7 Gc and then varying the frequency of the klystron to obtain the other TE_{01n} modes. The discrepancy between the calculated values and measured values above relates to the fact that the calculated values represent only the frequency of the simple right cylindrical cavity excluding the effects of the coupled resonator systems or the effects of the coupling mechanism. Modes other than the TE_{01n} modes were not detected since they are suppressed by the absorber shown in Figure 13. All the modes of the cavity except the TE_{01n} mode family have longitudinal components of current along the wall of the cavity. These currents flowing across the gap at the center of the cavity wall shown in Figure 13 will develop an E field across the absorber coupling slot which is in turn coupled to the absorber shown on the outer wall of the anode. This method of absorbing interfering non-TE_{01n} modes has proven quite successful.

The effect of the absorber on non-TE_{01n} modes is quite drastic, most of them becoming unmeasurable. The effect of this absorber on the TE_{01n} family of modes has been measured with the following results.

<table>
<thead>
<tr>
<th>Mode</th>
<th>With Absorber</th>
<th>Without Absorber</th>
<th>Percent decrease in Q_u</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE_{014}</td>
<td>5720</td>
<td>6650</td>
<td>14%</td>
</tr>
<tr>
<td>TE_{015}</td>
<td>1880</td>
<td>2435</td>
<td>23%</td>
</tr>
</tbody>
</table>

It can be seen from the values above that the TE_{015} mode is affected more than the TE_{014} mode. Since the cavity is an even number of half-wavelengths long, a null will always occur at the center for
modes containing an even number of half-wavelengths, whereas a maximum
will occur for all modes composed of an odd number of half-wavelengths.
Therefore, the region of maximum current for modes which are an odd
number of half-wavelengths long is always at the point where this
absorber is located. Conversely, for modes which are an even number of
half-wavelengths long, a minimum or null always exists at the absorber
location.

An experiment was conducted to determine whether the two sets
of vane resonators associated with the two-stage tube anode would be
equally excited. A dielectric sleeve was made which fitted snugly on
the outside diameter of the vane resonators. This dielectric sleeve
shifts the resonant frequency of the composite cavity-resonator system
an amount proportional to the magnitude of the energy stored in the vane
resonators. The composite system can be considered to be three inde-
pendent systems connected together. These three systems are the
cylindrical four half-wavelength long cavity, the set of vane resonators
near the tuner end of the cavity and the set of vane resonators near
the output end of the cavity. The two sets of vane resonators are
identical in design and are coupled to the cavity in the same manner.
As a result, the energy contained in each set of resonators should be
the same. If the dielectric sleeve is first placed around one set of
resonators and the change in resonant frequency is measured, placing
the same dielectric sleeve around the other set of vane resonators
should result in the same frequency change provided the amount of energy
stored in each set of vane resonators is equal. Early measurements
indicated that the energy stored in each set of resonators was not quite
the same. However, by controlling the length of slots which couple the
vane resonator system to the cavity, the energy in each set of vane
resonators could be made identical. This method of controlling the
excitation of the vane resonators can be used to preferentially load
or unload a set of vane resonators.
The first anode made for an operable tube was of the one-piece type. Since alignment of two separate anodes could present a problem during assembly, it was decided to make the two resonator sections on a common cavity. The anode sub-assembly may be fabricated before insertion into the tube body and then is bolted to the tube body. This provides anode interchangeability with a minimum of effort. Figure 14 is a photograph of this anode. Note the slot which provides coupling for the circumferential absorber described earlier.

The first one-piece anode was initially evaluated using a single disk tuning plunger which allowed us to observe the proximity of the adjacent TE_{01n} modes - namely, the TE_{013} and TE_{015} modes. With the cold tester adjusted to the TE_{014} cavity mode at a frequency of 34.3 Gc, the TE_{015} mode could be detected at 37.705 Gc. The TE_{013} mode could not be detected since it fell outside the tuning range of the klystron power source. In the TE_{014} mode cavity, the anode exhibited Q_u's of 1500 minimum over a 2 Gc band and Q_u's greater than 3000 over a 0.6 Gc band. When the TE_{014} mode was tuned to 36.105 Gc, the TE_{013} mode could be detected at 32.490 Gc. This places the optimum frequency of operation of the TE_{014} mode at about 34.5 Gc. The frequency proximity among the TE_{013}, TE_{014}, and TE_{015} modes agrees favorably with that calculated thus placing the nearest TE_{01n} mode more than 3.5 Gc away.

Having established the relative Q_u's of the circuit across the band in the TE_{014} cavity mode, a double disk tuning plunger was employed in subsequent tests. The two disks were located two half-wavelengths apart on the tuning rod thus forming two TE_{012} cavities coupled together. However when the tuning rod is moved for the purpose of tuning, it should be noted that the two disks on the rod remain the same distance apart irrespective of the tuner rod position and, therefore, yield only one frequency of operation. This is not true of the center disk with respect to the tuner end of cavity and thus the cavity associated with the tuner end resonator structure does change length and thereby frequency. Early experiments utilizing such a scheme on a TE_{012}
FIGURE 14  PHOTOGRAPH OF ONE-PIECE TWO-STAGE ANODE
hybrid cold test revealed that the $Q_u$'s measured appeared to represent
the $Q_u$ of the fixed tuned cavity rather than a composite $Q_u$ of the fixed
tuned and tunable cavities, apparently the result of insufficient
coupling between the cavities. The most logical way to increase the
coupling between the two cavities is to reduce the diameter of this
coupling disk. Intercavity coupling was increased in progressive steps
until the rate of change of the tuning curve indicated that the desired
coupling was obtained. The tuning plunger was used in the first two-
stage tube, the results of which are discussed in Section 5.2.

4.3 The Drag Loop

When the first double disk plunger was designed and made for
the first two-stage tube, cold test measurements revealed that a rapid
change in the tuning rate of the tunable cavity occurred near what was
felt to be the frequency of the fixed tuned cavity. That is to say,
that the tuning rate of the tunable cavity reduces drastically when it
approaches the apparent fixed tuned cavity frequency. In an endeavor
to explain this effect, different diameter disks were used with different
spacings between the two disks on the tuning plunger rod. From these
tests, it became apparent that the effect noted is what is often called
the "drag loop" in coupled circuit oscillators (Ref. 2).

The drag loop is formed when sufficiently close coupling is
employed between two resonant circuits so that two different frequencies
of operation can exist for a given LC ratio. With one resonant cavity
fixed tuned and the other resonant cavity approaching the fixed tuned
frequency from the lower frequency region, the frequency of operation
would "skip" from below the fixed tuned cavity frequency to above the
fixed tuned cavity frequency. Upon returning along the upper branch

2. Cruft Laboratory Staff, Harvard University, ELECTRONIC CIRCUITS
AND TUBES, McGraw-Hill Book Company, pp. 474-477,
1946 (1947)}
tuning curve, the downward "skip" occurs at a different cavity length, hence the loop is formed. The drag loop is somewhat similar to the hysteresis loop observed in magnetism. The size of the loop is dependent upon the amount of coupling between the cavities and for \( k < 1/Q_o \), the loop ceases to exist. Figure 15 shows the drag loop for three conditions of coupling between the cavities of the two-stage tube. They are \( k < 1/Q_1 \), \( k = 1/Q_2 \), and \( k > 1/Q_2 \).
FIGURE 15 DRAG LOOP
5.1 hybrid Tubes

The first hybrid tube (F32D) which was built without a stabilizing disk for reasons previously discussed, started in the desired TE$_{012}$ mode of the cavity at 34.565 GHz. This hybrid tube was made tunable to allow another degree of freedom in evaluating the device. Operation in the desired TE$_{012}$ mode could be maintained from 32.20 GHz to 35.95 GHz, a 3.75 GHz range. These results indicate clearly that a stabilizing disk is not required in a tube with a TE$_{012}$ mode cavity length.

This first hybrid tube (F32D), however, was limited to a peak power output of approximately 80 kW when operated at 0.5 µsec pulse length. A line type modulator similar to that used to operate the more conventional ICEM coaxial magnetron at 125 kW peak power output at 0.5 µsec pulse length was used. The power output was limited by increased jitter. Beyond this 80 kW level, the tube would not operate satisfactorily in the desired mode. Greater starting jitter was anticipated, however, because of the increased energy storage ratio mentioned previously. Figures 16 and 17 show these relative amounts of jitter between the TE$_{011}$ and TE$_{012}$ mode operation of the first hybrid tube as seen on the detected RF pulse. The frequency of operation was identical for the two test conditions.

To ascertain whether the increased jitter was associated with the increased energy storage ratio, the first hybrid tube (F32D) was operated into a mismatch of approximately 1.5:1 VSWR. The phase of the mismatch was adjusted to yield least jitter on the detected RF envelope. The best operating point corresponded to the anti-sink phase of the mismatch indicating that better performance could be achieved when the tube was delivering less power to the load.

To further substantiate the argument that the increased jitter is due to the increased energy storage ratio, the hybrid tube was tuned so that it operated in the TE$_{011}$ mode at 36 GHz. This means that the cavity is now one half-wavelength instead of two half-wavelengths long.
FIGURE 16 DETECTED RF OUTPUT PULSE OF FIRST HYBRID TUBE (F32D) OPERATING IN TE₀₁₁ MODE AT 120 kW LEVEL

FIGURE 17 DETECTED RF OUTPUT PULSE FOR FIRST HYBRID TUBE (F32D) OPERATING IN TE₀₁₂ MODE AT 80 kW LEVEL
Under these conditions, the hybrid tube generated over 100 kw peak power output with approximately 2 nsec RMS jitter. The results of this experiment indicated that the increased jitter is associated with the increased energy storage ratio.

The second hybrid tube (I6C) was built to evaluate ICEM coaxial magnetron operation in both the $\text{TE}_{012}$ and $\text{TE}_{013}$ modes. Since the first hybrid tube demonstrated that the starting jitter in the $\text{TE}_{012}$ cavity mode of operation was excessive, a slot length adjustment was made. A similar jitter problem was encountered in the standard ICEM coaxial magnetron but was solved by improving the coupling between the anode vane resonators and the cavity. The slot length adjustment employed on the second hybrid tube was an application of similar techniques.

The second hybrid tube operated very well in the $\text{TE}_{012}$ cavity mode (desired mode) at 34.4 Gc. The output power was 155 kw at an efficiency of 21.4% and the starting jitter was low. Figure 18 is a photograph of the detected RF pulse in the $\text{TE}_{012}$ mode of operation. This tube operated at nearly twice the power output level of the first hybrid tube in the $\text{TE}_{012}$ mode and yet demonstrated a reduction in starting jitter by a factor of five. At low power output levels (~25 kw) the second hybrid tube, operating in the $\text{TE}_{012}$ cavity mode, could be tuned from 30.64 Gc to 34.02 Gc (a band of 3.38 Gc) with no mode competition from adjacent $\text{TE}_{01n}$ modes ($\text{TE}_{011}$ and $\text{TE}_{013}$). However, if the tube was tuned to frequencies lower than 30.34 Gc in the $\text{TE}_{011}$ cavity mode, oscillations would cease at 30.14 Gc ($\text{TE}_{012}$ mode) and shift to 34.59 Gc - the $\text{TE}_{013}$ cavity mode.

The second hybrid tube was then adjusted for $\text{TE}_{013}$ cavity mode operation at 34.5 Gc. The starting jitter in the $\text{TE}_{012}$ mode of operation was greater than that exhibited in the $\text{TE}_{011}$ mode by a factor of two but was still a reasonably low value and did not begin to limit operation until the 112 kw power output level was reached. Figure 20 shows the detected RF pulse with the jitter clearly visible. Figure 5 shows expanded sweep photographs for the purpose of jitter measurements. The
FIGURE 18  DETECTED RF OUTPUT PULSE OF SECOND HYBRID TUBE (I6D) OPERATING IN $\text{TE}_{012}$ MODE AT 155 kW LEVEL

FIGURE 19  DETECTED RF OUTPUT PULSE OF SECOND HYBRID TUBE (I6D) OPERATING IN $\text{TE}_{013}$ MODE AT 112 kW LEVEL
FIGURE 20  DETECTED RF OUTPUT PULSE OF SECOND HYBRID TUBE (16D) SHOWING PEAK-TO-PEAK STARTING JITTER IN TE₉₀₁₃ MODE
peak-to-peak jitter of Figure 20 is 30 nsec. This tube could be tuned from 32.2 Gc to 34.8 Gc in the TE_{013} cavity mode (a 2.6 Gc band) without TE_{012} or TE_{014} mode competition. This again indicated that the starting jitter is a function of the energy storage ratio.

5.2 Two-stage Tubes

The first two-stage ICEM coaxial magnetron (J25D) was received for evaluation in November 1962. Some difficulties were encountered in the assembly and brazing of the anode sub-assembly. Figure 21 is a photograph showing the complexity of this sub-assembly. Eight separate brazes are made in one operation while maintaining the close tolerances dictated by the frequency of operation. Figure 22 is a photograph of the complete two-stage tube.

Initial tests consisted of seasoning each section of the two-stage tube separately. When operated alone the section nearest the output did not operate in a completely conventional manner. The output power was low and the frequency of the output was not adjustable. Evidently the coupling between the sections was not sufficient to have the coupled cavity become a frequency determining element in the composite system. The tunable section operated in a manner similar to that of a single-stage ICEM coaxial magnetron except at the frequency coincident with the frequency of the fixed tuned section of the tube. At low drive levels where the cavity frequencies are coincident, no output power was detectable. However, as the input drive was increased, output power was realized being accompanied by relatively high starting jitter. The starting jitter reduced as the input drive was increased further and nearly disappeared when the tunable section was shifted in frequency away from the fixed tuned section.

Upon pulsing both sections simultaneously using a separate modulator for each section and operating both sections at the same frequency, additive output power was measured. The total output power was 16.5 kw at 0.45 μsec and 0.0002 duty cycle. The tunable section contributed
FIGURE 21  PHOTOGRAPH OF TWO-STAGE ANODE SUB-ASSEMBLY
FIGURE 22  PHOTOGRAPH OF FIRST TWO-STAGE TUBE (J25D)
about 70% of the total power. Then the tunable section was operated at a 60 kw level while the fixed tuned section had neither pulse power nor heater power applied. Next the fixed tuned section was pulsed but the cathode remained unheated. The total output power yielded by the two-stage tube with both sections operating was 45% greater than the power derived from the tunable section alone. Figure 23 shows the detected RF output pulse and Figure 24 shows the detected RF output pulse with both sections operating additively. This cold cathode operation is very encouraging and lends credence to the theory that a cold cathode oscillator amplifier type combination is feasible.

An interesting application of the cold cathode phenomenon to a multistage ICEM coaxial magnetron is one of having the cold cathode section generate more power than the hot cathode section. Since the hot cathode section has excellent starting characteristics and the cold cathode section poorer starting characteristics but high power capabilities, the tube can be operated to enhance the attributes of each. The hot cathode section would be pulsed just a nanosecond or two before the cold cathode section thus allowing the RF fields at the vane tips in the cold cathode section to build up and thereby "lock" the cold cathode section RF build up to the desired mode.

Further evaluation revealed the fact that both sections could be operated together but at somewhat different frequencies. This could be accomplished at a 50 kw power level above which some arcing existed. Since the output section is fixed tuned but the tuner section of the tube is tunable, separate frequency operation could be obtained over a 200 Mc band. That is to say, that two output frequencies were obtained simultaneously with a frequency separation as great as 200 Mc. Although this is not a direct aim of this contract, the possibility of evolving a frequency diversity radar system using this type of operation is perhaps possible.

The second two-stage tube A1-E, which was completed for evaluation in January 1947, initially showed greater than normal amounts
FIGURE 23 DETECTED RF OUTPUT PULSE OF FIRST TWO-STAGE TUBE (J25D) WITH ONLY TUNABLE SECTION BEING PULSED

FIGURE 24 DETECTED RF OUTPUT PULSE OF FIRST TWO-STAGE TUBE (J25D) WITH BOTH SECTIONS OPERATING
of starting jitter when seasoning was attempted. This tube incorporated
ing engineering changes designed to facilitate mechanical assembly, namely
a modification of the anode support assembly which eliminated the circum-
ferential slot and the circumferential absorber. This absorbing mechanism
was designed to inhibit non-TE$_{01n}$ cavity modes. Since the first two-stage
tube (J25D) exhibited no apparent non-TE$_{01n}$ mode contamination, the
exclusion of this absorber seemed possible. To help offset the lack of
non-TE$_{01n}$ mode suppression, the axial anode coupling slots were shortened
to provide tighter coupling between cavity and vane resonators to enhance
desired mode operation. From a mechanical standpoint, this simplified
the anode machining operation.

As testing of tube Al3E progressed, the starting jitter became
excessive and slot mode operation appeared. Cathode eccentricity is a
known cause of slot mode operation. It was planned to open this tube
and measure the concentricity of the cathode with respect to the anode,
but during the concluding operational tests the tuning plunger seized.
These problems, compounded, prompted the decision to discontinue evalu-
ation of tube Al3E since they were basic to general magnetron operation
and not peculiar to the two-stage device.

To expedite the program with regard to hot test evaluation,
the first two-stage tube (J25D) was rebuilt incorporating a modified
tuning plunger. The modified tuning plunger is also a two disk plunger
but, unlike the original plunger which formed two full-wavelength
cavities, the modified plunger forms a single half-wavelength cavity
and a three half-wavelength cavity. The single half-wavelength cavity
provides the desired starting characteristics in the tunable section
of the tube while the three half-wavelength cavity section provides a
source of high output power without the consequence of poor starting
characteristics.

The rebuilt two-stage tube (J25D-R) demonstrated operation
which was very encouraging. The output power measured with both sections
operating simultaneously (at the same frequency) was 1.8 kw and no
measurable starting jitter was encountered. When the tunable section (TE\textsubscript{011} cavity) was operated alone - at the frequency of the fixed tuned section - excessive jitter was encountered. However, upon application of pulse voltage to the output section of the tube, the starting jitter disappeared and additive power output was realized. Approximately 54% of the total power output was derived from the output section of the tube. This test was performed at a low output level (0.70 kw total) because operation of the tuner section alone at high levels is not possible. Figure 25 is a photograph of the RF spectrum with both sections operating.

The third two-stage tube (B27E) completed late January 1963 exhibited extremely high gas pressure. Repeated bakeouts only partially alleviated the problem. Since time was at a premium, electrical evaluation was begun even though the desired vacuum was not attained. Electrical tests showed that the two sections of the tube operated at considerably different voltages and arcing occurred at low power levels. The arcing was undoubtedly the result of the poor vacuum attained. Further evaluation of tube B27E was abandoned so that maximum effort could be devoted to the last two-stage tube (C8E) received for electrical evaluation in February 1963.

Tube C8E was similar to the rebuilt tube (J25D-R) except for the fact that increased coupling to the load was employed. The output power obtained with both tube sections operating simultaneously (at the same frequency) was 158 kw and very low starting jitter was encountered. It appeared that more than 50% of the output power was derived from the tunable section of the tube but this is an estimate since the tunable section cannot be operated alone without large amounts of jitter being present.
FIGURE 26  SPECTRUM DISPLAY OF TUBE J25D-R WITH BOTH SECTIONS OPERATING
C.0 TEST EQUIPMENT

C.1 Q Measuring Equipment

The TE_{01} circular waveguide size used in the Ka-band TEM coaxial magnetron was selected from the Electronic Industries Association Standard RS-200 published January 1958. The size selected for Ka-band for operation in the TE_{01} mode is WR52, which is 0.594 inch ID. The tolerances of the waveguide are as described in EIA Standard RS-200.

A photograph of the Q measuring set is shown in Figure 27', and the schematic of the Ka-band test set is shown in Figure 27. The method used to measure \( Q_u \) and \( Q_e \) is known as the Reed (Ref. 3) method. All components used in the Q measuring set are commercially available and are identified in the schematic diagram. The only item that required modification was the Microwave Associates Transition from TE_{10} rectangular to TE_{01} circular guide. This transition is a four slot end feed transition with a tapered circular waveguide on the output end. The inside diameter of this circular guide is 0.634 inch. Since the guide selected from EIA Standard RS-200 is only 0.594 inch ID, it was necessary to cut the tapered circular guide section until the ID was 0.594 inch and then attach a flange which would mate with the tube output. This flange insures lineup of the two sections of waveguide. However, a good contact between the two sections is not required since no current will flow across this joint in the TE_{01} circular-electric mode.

C.2 Hot Test Equipment

The Ka-band test set used to measure the operating performance of the tubes is shown schematically in Figure 28. An electromagnet is used to supply the variable magnetic field required for performance tests.

FIGURE 26  PHOTOGRAPH OF KA-BAND Q MEASURING TEST SET
FIGURE 27 SCHEMATIC OF KA-BAND
AND Q MEASURING TEST SETUP

- HP R752C
- HP R752C
- HP R870A
- Slide screw tuner
- Waveline 1000
- Shorting switch
- SPD-801 transition
- SPD-301
- ICOM coaxial magnetron
ICEH coaxial magnetron

SFD Ka-band
directional

HP 8532A
frequency
meter

Figure 26 Schematic of Ka-Band Tube
A directional coupler was designed to couple power from the $T_{\nu_1}$ circular guide to the dominant mode rectangular guide and is similar to the one shown in Figure 74 of WADC Technical Report 58-661. The directivity and accuracy of coupling was not important since it was desired only to view the RF envelope of the pulse using standard rectangular waveguide components commercially available. A 40 db directional coupler was built for the Ka-band test set.

To measure the power generated by the ICEM coaxial magnetron, a water load was designed by S-F-D laboratories and built by Chemalloy Electronics Corporation. It consists of a long tapered glass tube flaring out to the inside diameter of the waveguide in a distance of 15 wavelengths. The tapered glass water load is inserted into a section of circular waveguide and the average power generated by the magnetron is measured with a calorimeter. The water load was checked to ascertain that all the power was being absorbed in the load by holding a crystal detector at the end of the glass water load while the tube was generating approximately 100 kw peak power. There was no indication of power leakage at this point. By comparing this load on the Q test set to the yellow pine wood load described in WADC Technical Report 58-661, the VSWR is less than 1.05 at the desired operating frequency. The accuracy of the calorimeter was checked by substituting a water heater for the water load, heating the water with ac power and comparing the power read on the calorimeter with the ac input power as read on a precision wattmeter.

The two modulators designed and built by S-F-D laboratories under Air Force Contract AF 33(616)-7130 were used to operate the two-stage device. The two-stage Ka-band test vehicle could incorporate one hot and one cold cathode but initially two hot cathodes were used. The cathodes were pulsed separately by the two modulators. The various combinations of pulsed operation investigated are

1. Synchronized pulse two-stage operation
2. Overlapped pulse two-stage operation.
These modulators are of the line type, capable of supplying a 1.2 megawatt, 3.0 μsec pulse to a 500 ohm load at a 0.001 duty cycle. The pulse length can be varied in steps by changing the strap value of the pulse forming network. The pulse lengths available are 0.25, 0.5, 1.0, 2.0, and 3.0 μsec. A duty cycle of 0.001 can be used at all pulse lengths except 0.25 μsec since at this pulse length the Pb factor of the thyatron will be exceeded. The trigger generator is capable of supplying the necessary repetition rate to operate at 0.001 duty cycle namely 133 pps to 2000 pps. The modulator may also be triggered by an external positive or negative 40 volt pulse.

It was necessary to completely rebuild the trigger source of one of the units. This was done so that dual cathode followers could be incorporated to yield the low output impedance necessary for impedance matching to the continuously variable delay lines. The continuously variable delay lines permit exact synchronization or advance or delay of either of the input pulses. Figure 29 is a block diagram of the pulsing scheme used.
FIGURE 29 BLOCK DIAGRAM SHOWING SYNCHRO
CHRONIZED PULSING SCHEME USED FOR TWO-STAGE TUBES
8.0 RECOMMENDATIONS

The feasibility of the two-stage ICEM coaxial magnetron has been demonstrated. Several models were constructed and tested. The maximum power output generated was in the order of 150 kw. This represents a significant power at 35 Gc but is nowhere near the full capability of this device. A single-stage ICEM coaxial magnetron has been operated at a peak power output of over 250 kw. Therefore, this two-stage device should be capable of generating powers in the vicinity of 500 kw at 35 Gc. The basic competing mode problems have been studied and the interference from these modes reduced. However, in order to realize the full capabilities of the two-stage device, a further study program is recommended. The program might include one or several of the following studies.

(1) A study of the output section of the two-stage tube. This tube can be considered to consist of two sections, an oscillator section and an amplifier section. The oscillator section is well understood since it is basically a single-stage ICEM coaxial magnetron. The output or amplifier section, however, is a relatively new concept and requires further study. This program might consist of making two separate tubes, one a standard ICEM coaxial magnetron and the other an output section consisting of one or more amplifier sections, each capable of adding approximately 3 db more power. This would decrease the complexity of the tubes since the oscillator and amplifier sections could be made in separate vacuum envelopes.

(2) A program to further investigate the two-stage ICEM coaxial magnetron in its present design configuration of oscillator and amplifier sections in one vacuum envelope. The performance
goal of this study might be the generation of 400 kW to 500 kW peak power output at Ka-band.

(3) A program to investigate the two-stage device as a means of generating high peak power output at frequencies of 70 GHz and above.