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AXIALLY EXTENDED INTERACTION AREA
INVERTED COAXIAL MAGNETRON

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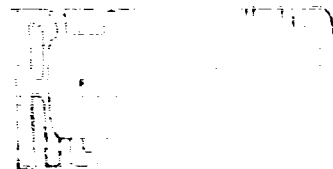
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FOREWORD

This Technical Documentary Report was prepared by S-F-D laboratories, inc., Union, New Jersey, on Air Force Contract AF 33(657)-8290, LPSN 2670-4156, entitled "Applied Research on Exten'ed Interaction in ICEM Magnetron." The work was administered under the direction of Electronic Technology Laboratory, Aeronautical Systems Division, presently designated Electronic Technology Division of the AF Avionics Laboratory of Research and Technology Division. Lt. M. Heil was project engineer for the laboratory.

The report summarizes the results of a twelve month feasibil_y 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.

The chief contributors and their fields of interest were: F. A. Feulner and P. du Fossé, electrical design and M. Liscio, mechanical design.

This report is the final report and concludes work on Contract AF 33(657)-8290. The contractor's report number is 20-F.

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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 $TE_{01(n\pm1)}$ 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 ICEM® 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 18 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 ICEM coaxial magnetrons through the use of the TE_{011} mode cavity. Since the principles of operation of the CEM and ICEM 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_{C11} 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 π mode.

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CURRENT FLOW

TE011 MAGNETIC
FIELD DIRECTIONS

ELECTRIC FIELD
ANTINODE

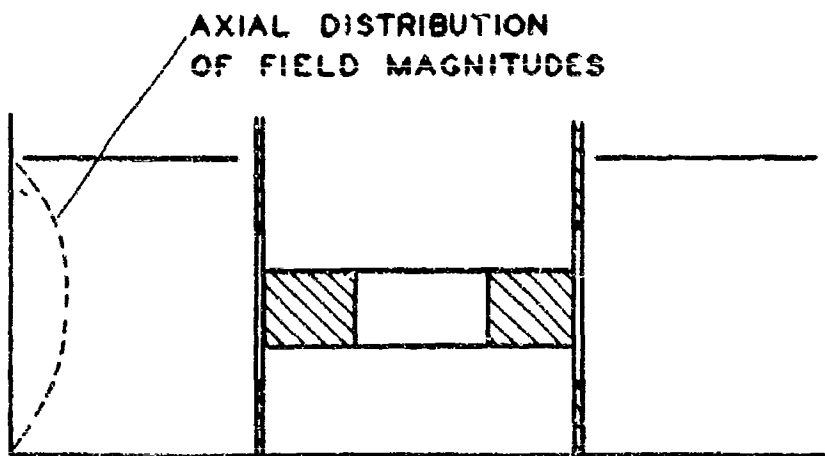AXIAL DISTRIBUTION
OF FIELD MAGNITUDES
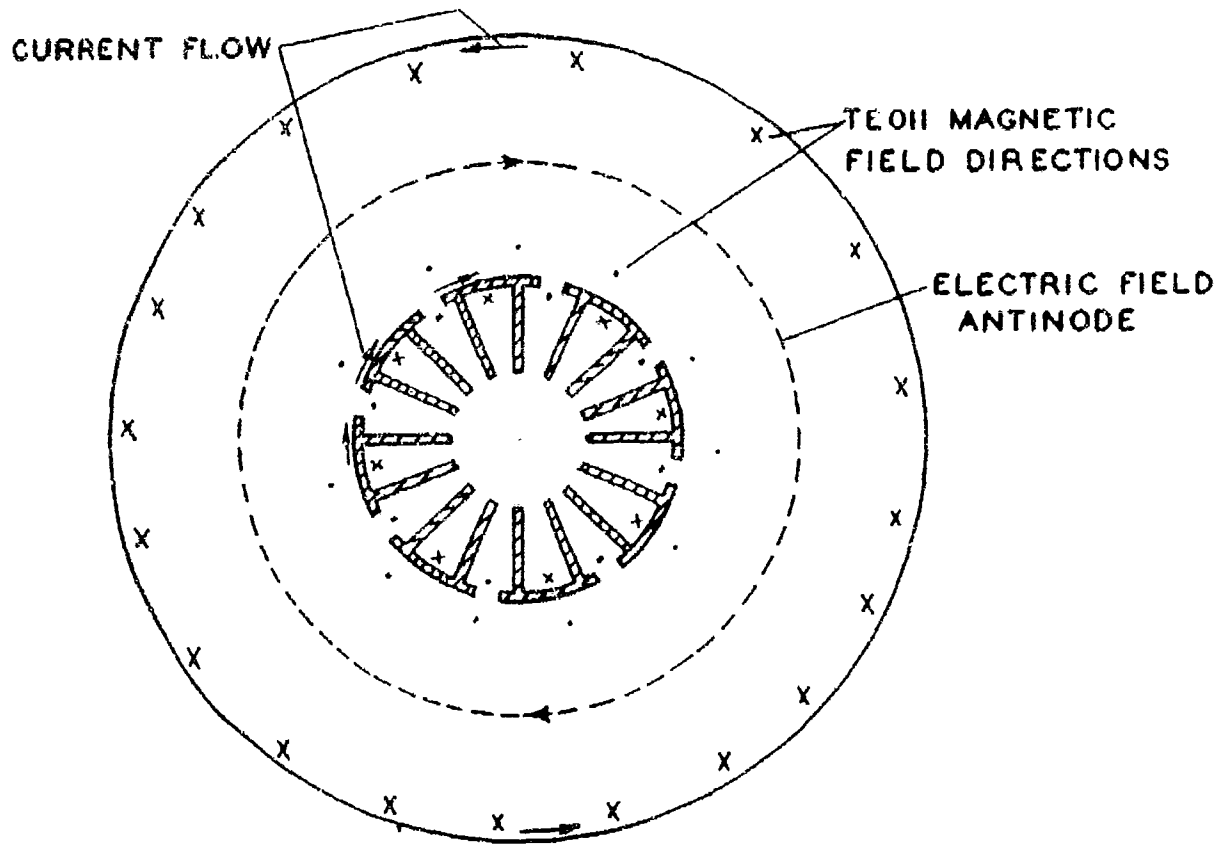
FIGURE 1   ANODE STRUCTURE OF THE CEM COAXIAL MAGNETRON

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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.
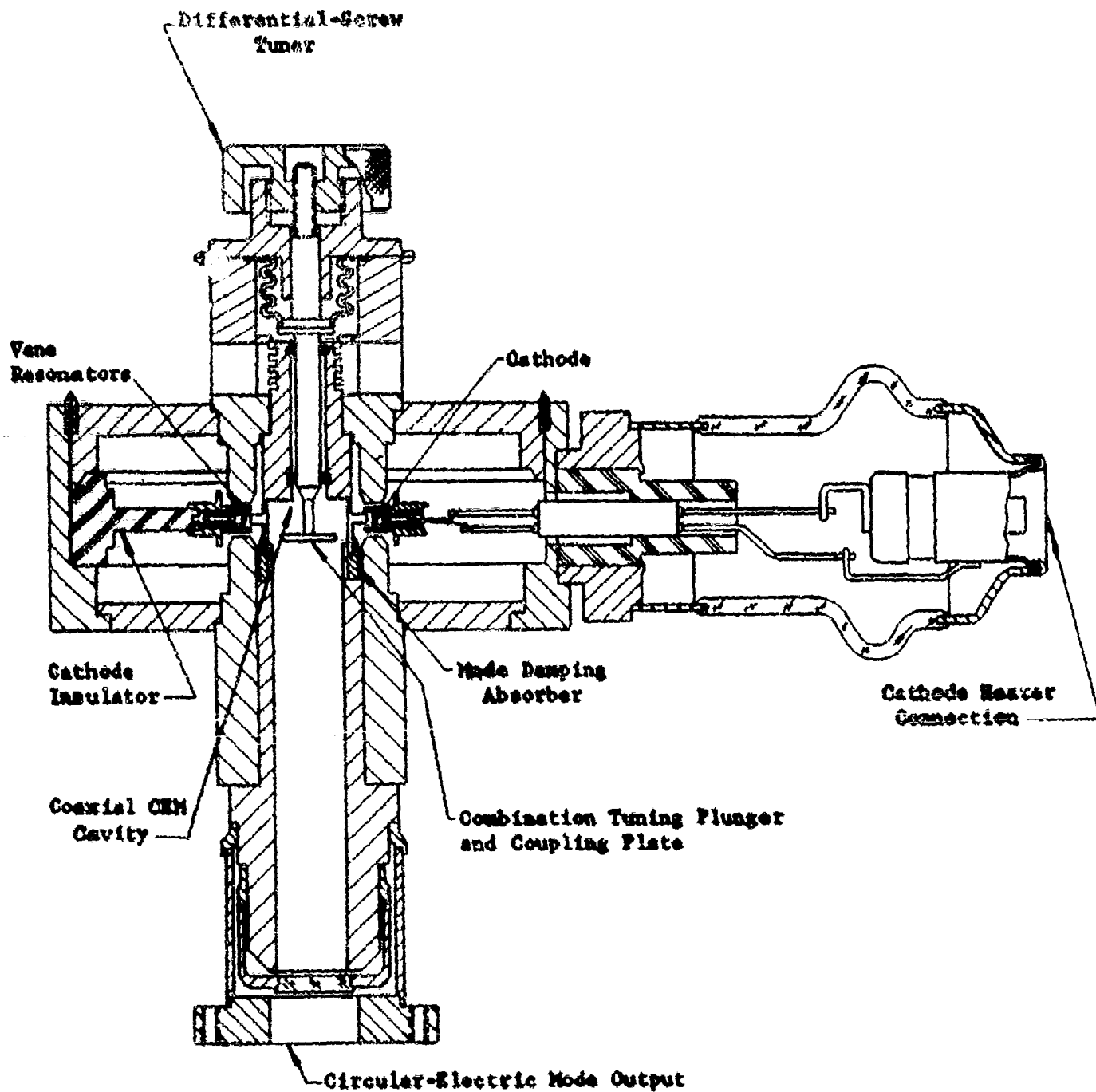
FIGURE 2   CROSS-SECTION OF TUNABLE ICEM COAXIAL MAGNETRON

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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.

32 Resonators   120 Resonators

TE$_{011}$ Cavity

Vane Resonators

Cathode

FIGURE 3   A COMPARISON OF A 32 VANE RISING-SUN STRUCTURE AND A
            120 VANE ICEM STRUCTURE

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2.0 INTRODUCTION TO THE EXTENDED INTERACTION ICEM COAXIAL MAGNETRON
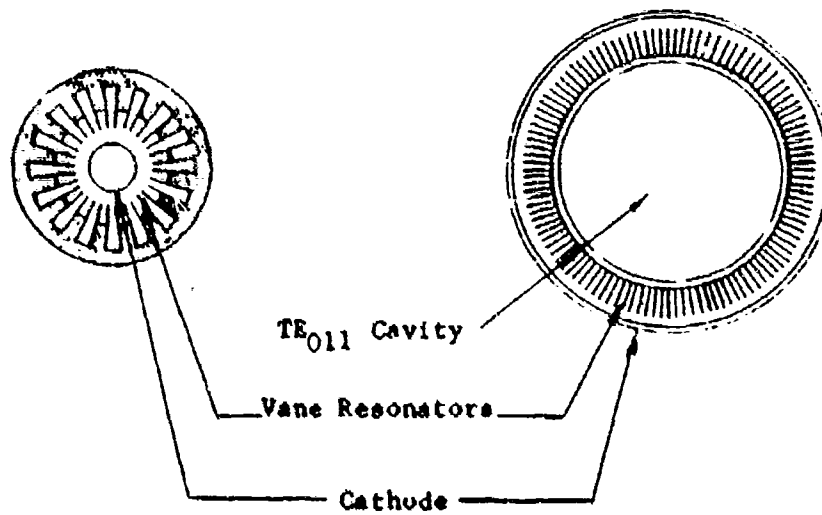
The main cavity resonator presently used in the single-stage ICEM coaxial magnetron is one half-wavelength long and operates in the TE_{011} mode. A cavity resonator could also be built which would operate in the TE_{012} mode and would, therefore, be a full wavelength long. One could conceive of using 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 cabity. 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_{01n} 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 4 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 heliarced to form vacuum seals.

Tuner

Resonant CEM Cavity TE_{015} or TE_{016}

Heated Cathode

Cathode Stem

Absorbers

Cold Cathode

Star-shaped Coupling Plate

Cathode
Insulators

Magnets

Packaged Tube

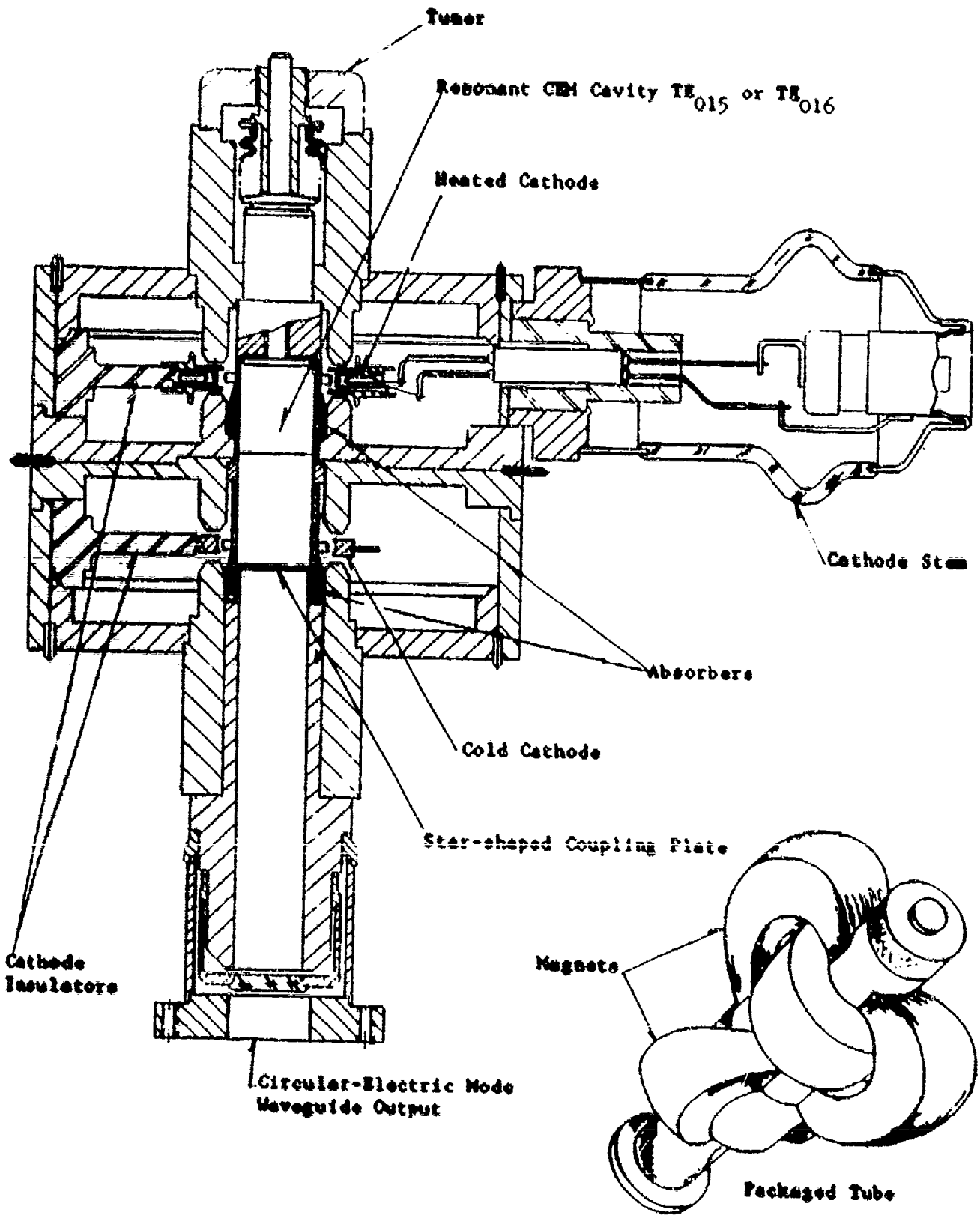Circular-Electric Mode
Waveguide Output

FIGURE 4   CROSS-SECTION OF TWO-STAGE ICEM COAXIAL MAGNETRON

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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 TE_{021} or TE_{0m1} mode and would have 2 or "m" times as many resonators as in the case of the 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 $TE_{0,m+1,1}$ mode without affecting a desired $TE_{0,m,1}$ 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 TF_{041} 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 ideal 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 arrange-
ment 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 signi-
ficantly reduced. Where the parallel gap arrangement results in a TE_{017}
mode cavity, the series gap arrangement results in a TE_{014} mode cavity.

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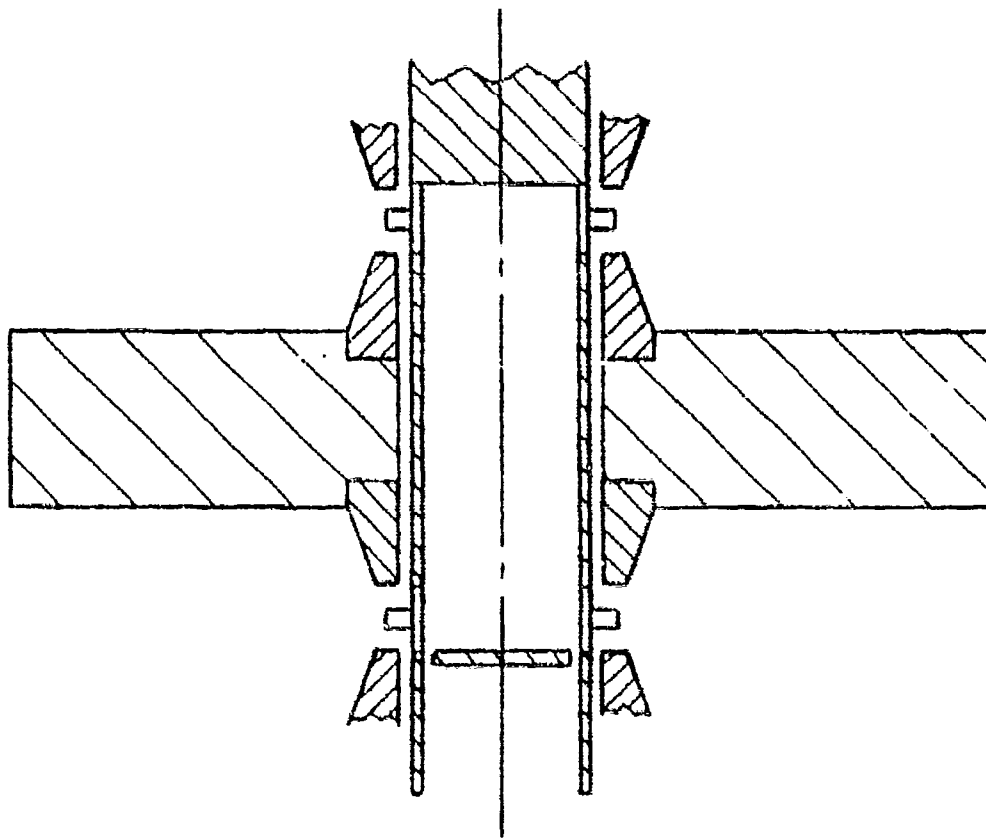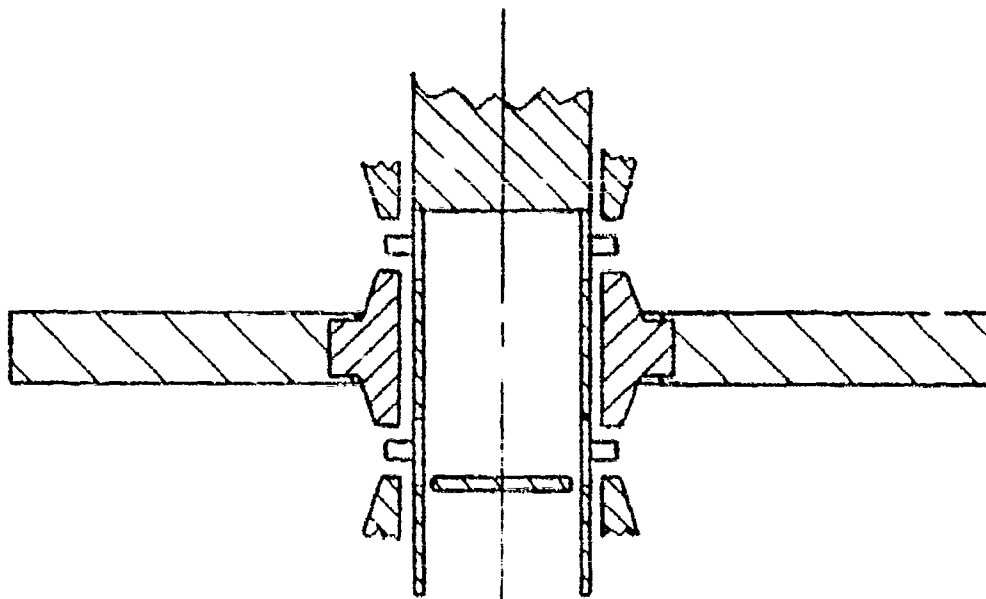
TE_{017}

TE_{014}

FIGURE 5 COMPARISON OF PARALLEL AND SERIES FED MAGNETIC CIRCUIT

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The mode separation of the TE_{01n} modes in a TE_{014} mode cavity is considerably greater than in a TE_{017} mode cavity. Figure 6 shows the proximity of the TE_{013} and TE_{015} modes in a cavity selected for TE_{014} mode operation. The equation (Ref. 1) for plotting a theoretical mode chart is

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

where

f = frequency in megacycles

D = diameter of cavity in inches

L = length of cavity in inches

n = mode number

$B = 0.348 \times 10^8$

$A = 2.07 \times 10^8$ for TE_{01} family

A sample calculation might be helpful at this point:

(1) in a full wavelength TE_{012} cavity where $(D/L) = 1.165$, the frequencies of the desired and adjacent TE_{01n} modes, when substituting in the above equation, are for

n = 1	f = 29.7 Gc
n = 2	f = 35.0 Gc
n = 3	f = 44.1 Gc

(2) in a two wavelength TE_{014} cavity where $(D/L) = 0.598$, the frequencies of the desired and adjacent modes are for

n = 3	f = 31.2 Gc
n = 4	f = 35.0 Gc
n = 5	f = 39.8 Gc

(3) in a three and one half wavelength TE_{017} cavity where $(D/L) = 0.335$, the frequencies of the undesired and adjacent modes are for

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1. Bell Telephone Laboratories Staff, RADAR SYSTEMS AND COMPONENTS, D. Van Nostrand Company, p. 912 (1949)
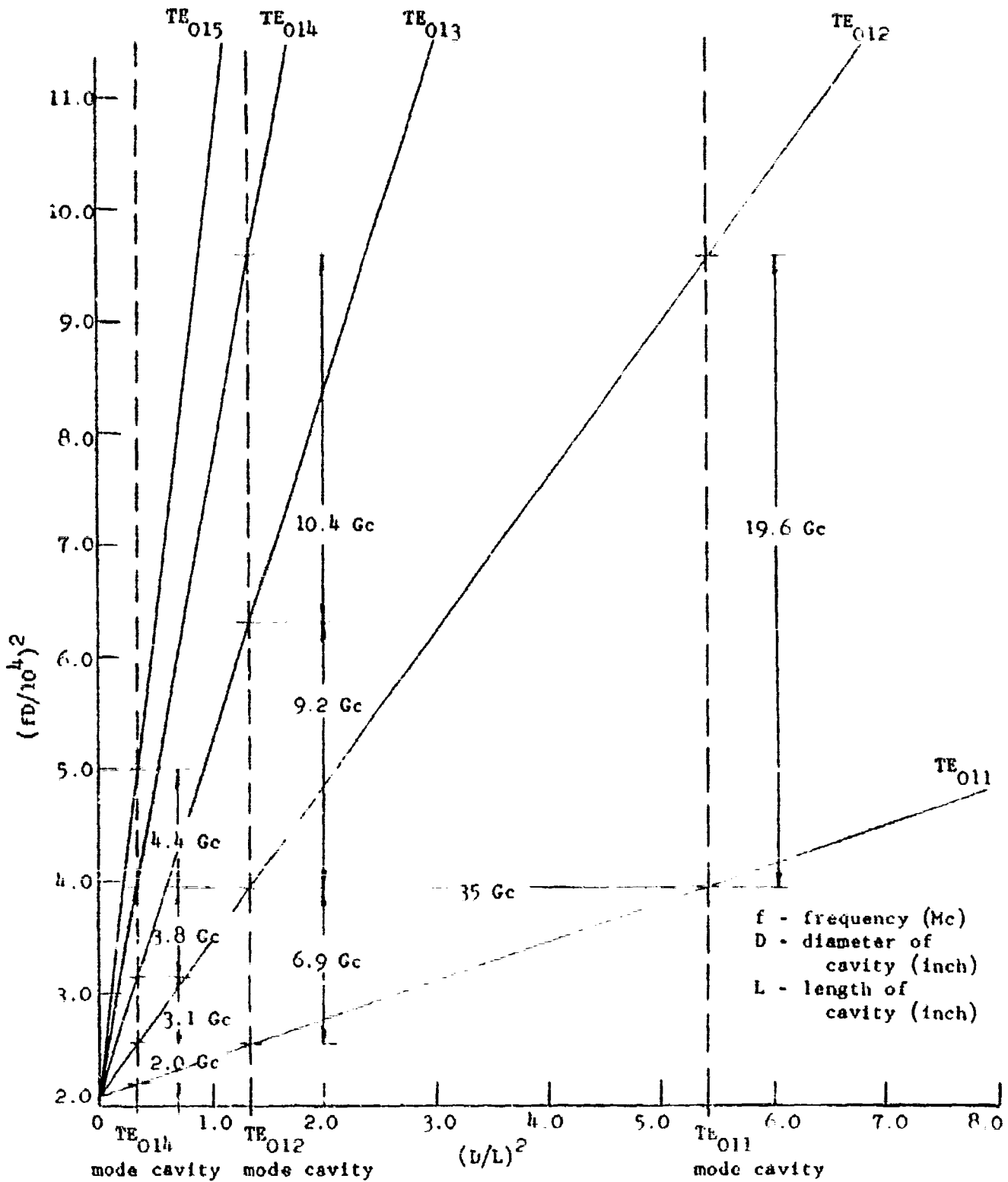
FIGURE 6 CHART SHOWING PROXIMITY OF TE$_{01p}$ MODES FOR CAVITIES DESIGNED
TO BE 1, 2 AND 4 ELECTRICAL HALF-WAVELENGTHS LONG AT 35 Gc

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$$n = 6 \qquad f = 32.8 \text{ Gc}$$
$$n = 7 \qquad f = 35.0 \text{ Gc}$$
$$n = 8 \qquad f = 37.5 \text{ Gc}$$

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 TE_{01n} 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 $TE_{\ell mn}$ modes of the non-TE_{01n} type have longitudinal wall currents while the TE_{01n} modes have only circumferential wall currents (of course, all TE_{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-TE_{01n} mode currents but not TE_{01n} mode currents. In addition, if behind this circumferential slot suitable absorbing material were placed, all the non-TE_{01n} mode Q_u's would be reduced.

3.3 The Hybrid Tube Test Vehicle

In the conventional single-stage ICEM coaxial magnetron, a single set of vane resonators is coupled to a circular cavity one electrical half-wavelength long. In the proposed two-stage ICEM 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_{014} 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

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competing TE_{01n} modes, namely the TE_{013} and 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 TE_{01n} mode frequency when a competing TE_{01n} 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.
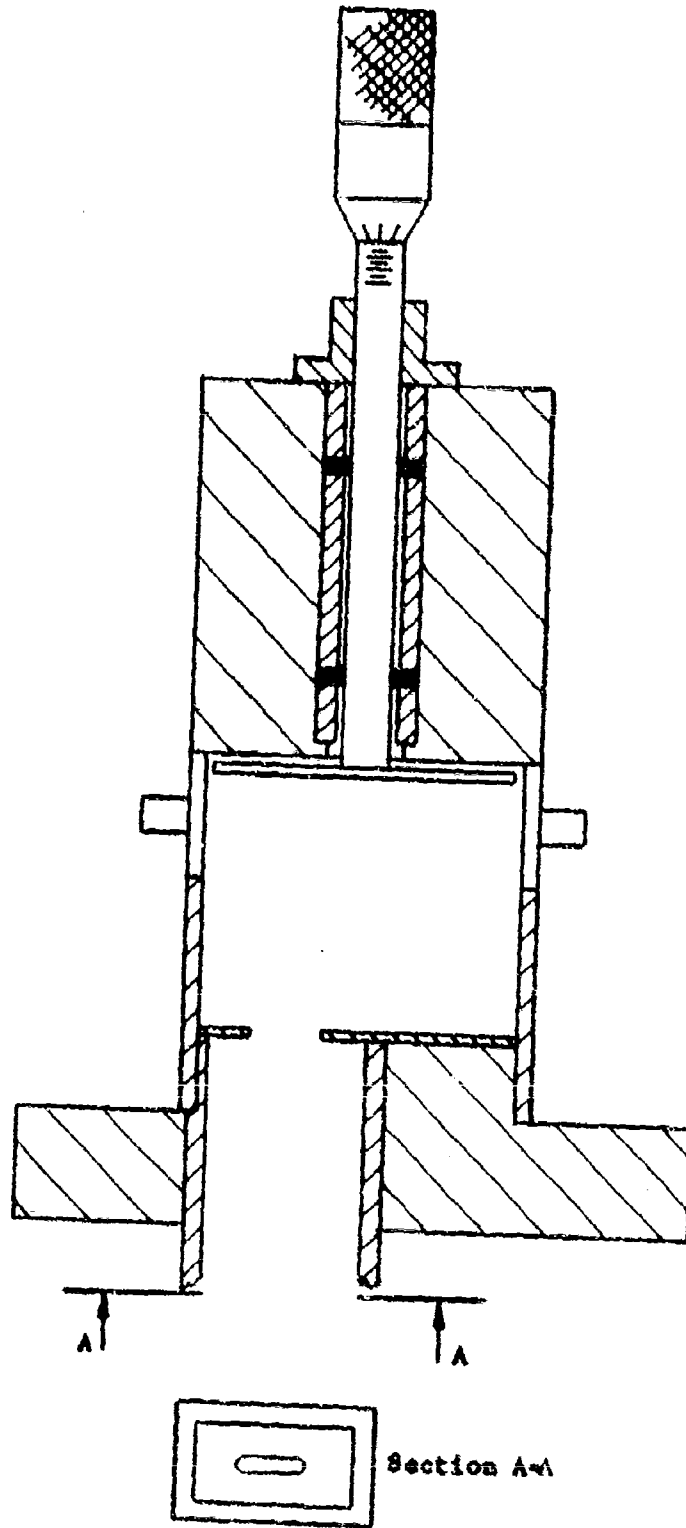
Section A-A

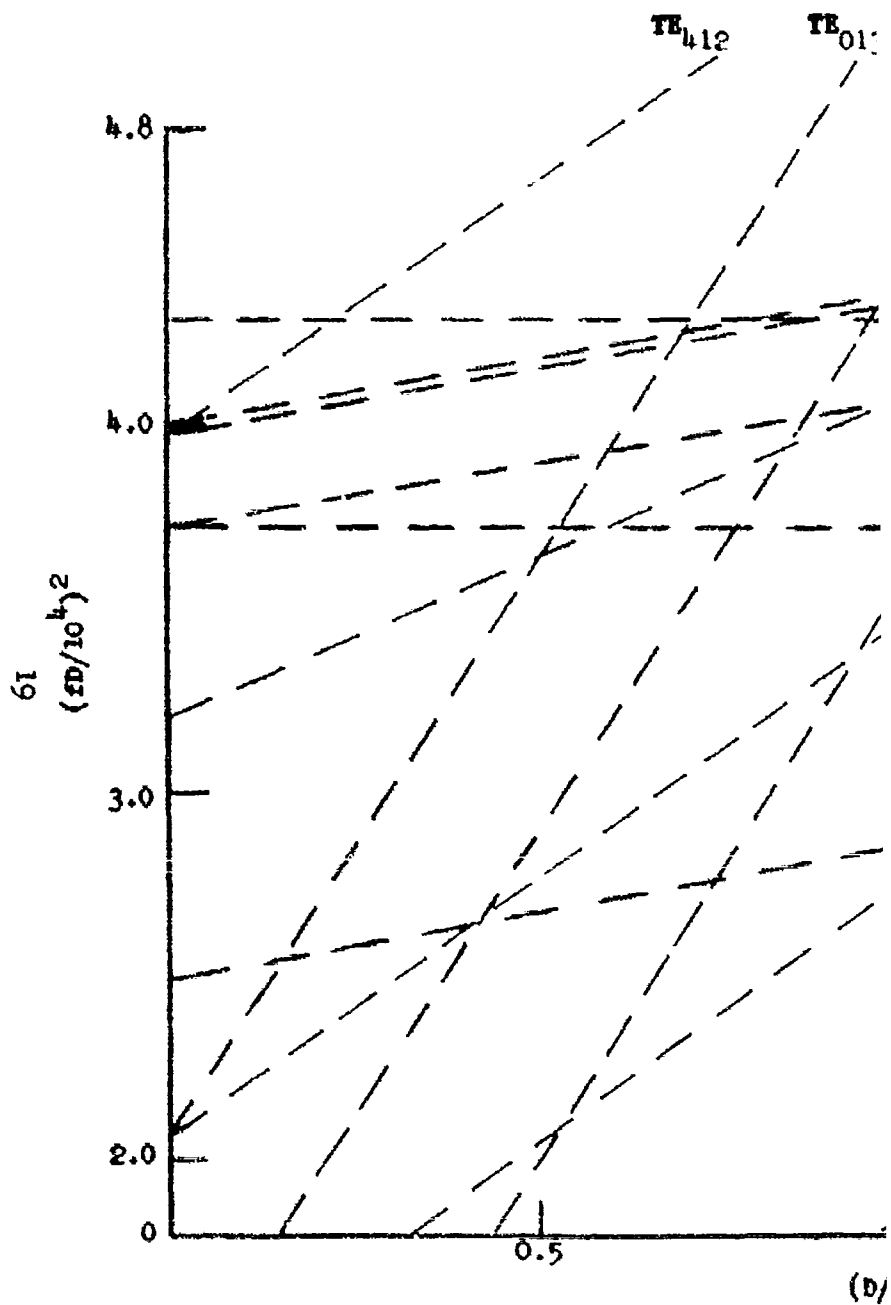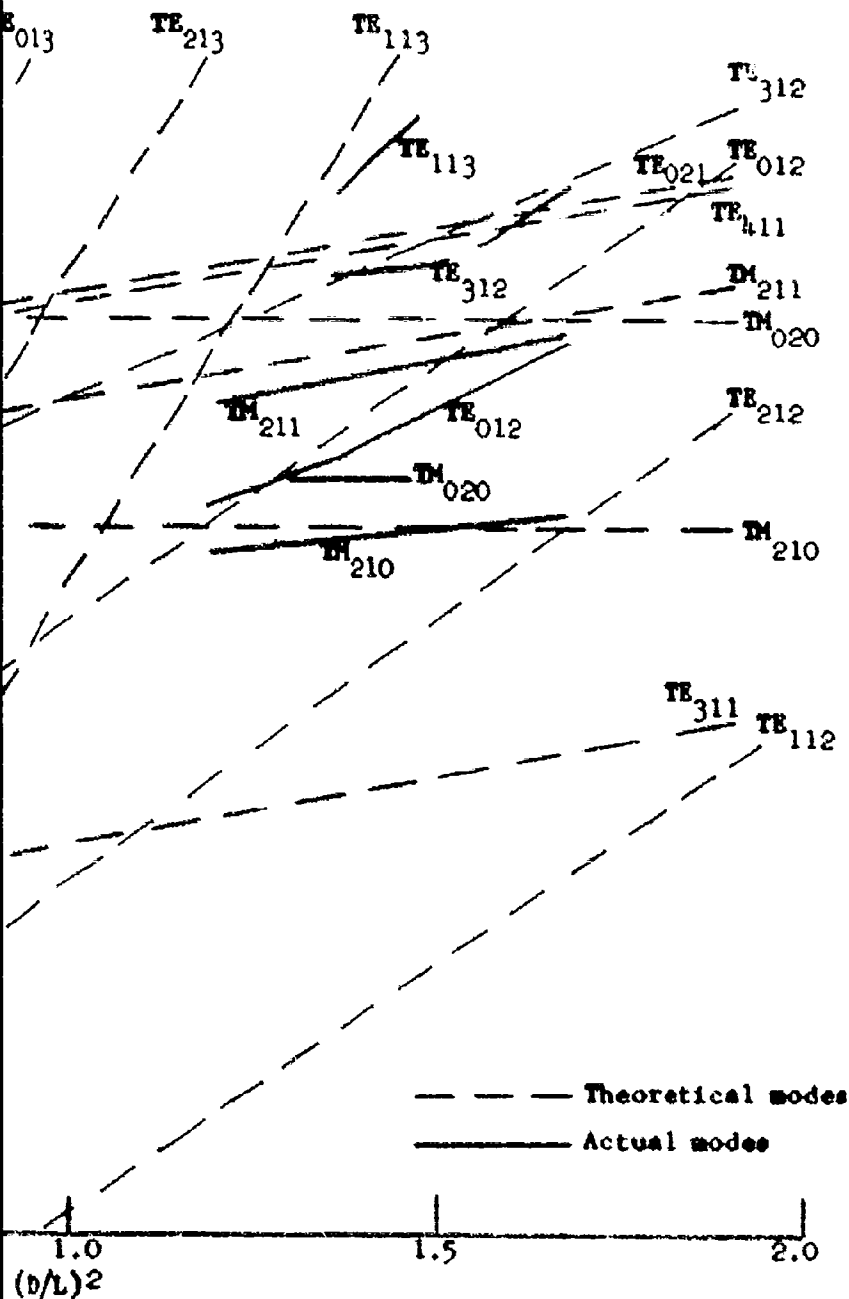FIGURE 7   CROSS-SECTION OF TE_{012} CAVITY COLD TESTER

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FIGURE 8 TE_{012} C

CAVITY MODE CHART

A hybrid tube cold test vehicle was then constructed to determine the relative values of Q_u for the various TE_{01n} 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 TE_{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 TE_{013} mode of the hybrid tube could not be found because the klystron used was limited to a 40 Gc upper frequency and the theoretical frequency of the TE_{013} mode is 44.2 Gc. However, the TE_{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 TE_{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., TE_{011} or TE_{013} mode operation in a cavity designed to operate in the TE_{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 TE_{011} and TE_{013} modes. A sketch of the cross-section of a TE_{01n} mode cavity along with the axial current distribution for the TE_{011}, TE_{012} and TE_{013} modes is shown in Figure 9.
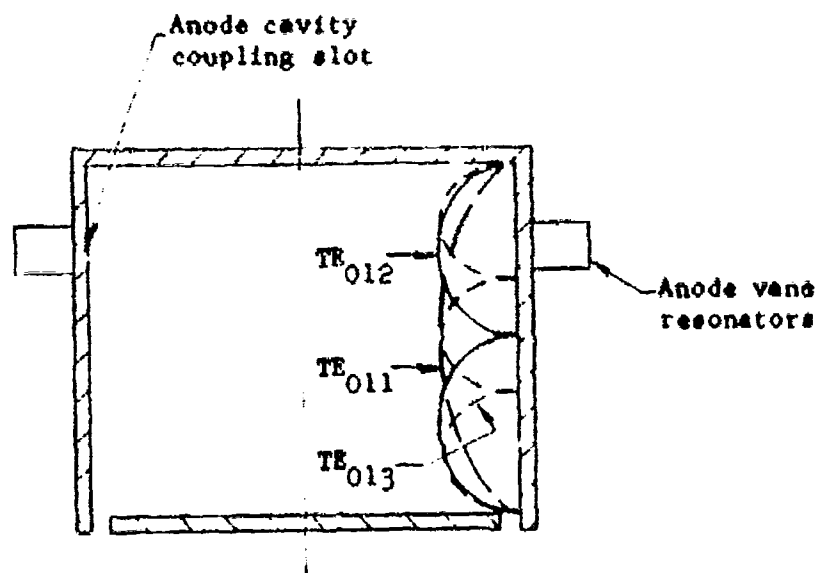
FIGURE 9   CROSS-SECTION OF A TE_{01n} MODE CAVITY SHOWING
THE AXIAL CURRENT DISTRIBUTION FOR THE TE_{011},
TE_{012} AND TE_{013} MODES.

In the hybrid tube, the competing TE_{01n} 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_{01n} 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 2690 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_{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_{014} mode. The tunable feature, as in the TE_{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 $TE_{\ell mn}$ modes of the non-TE_{01n} type have longitudinal wall currents while the TE_{01n} modes have only circumferential wall currents (of course, all $TE_{\ell mn}$ modes have longitudinal wall currents). Hence, if

FIGURE 10   PHOTOGRAPH OF A TUNING PLUNGER SHOWING
THE OUTPUT COUPLING DISK AND THE
STABILIZING DISK

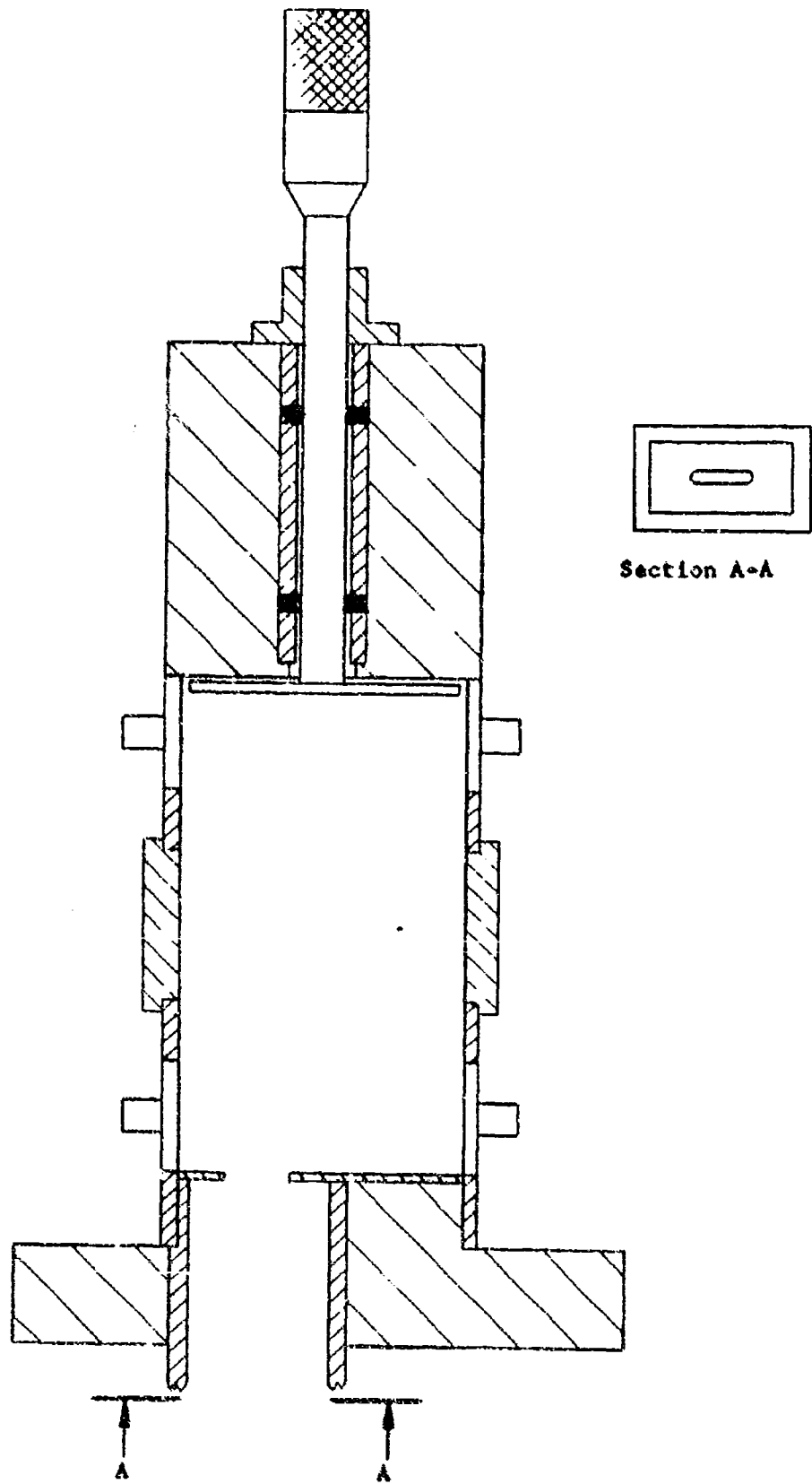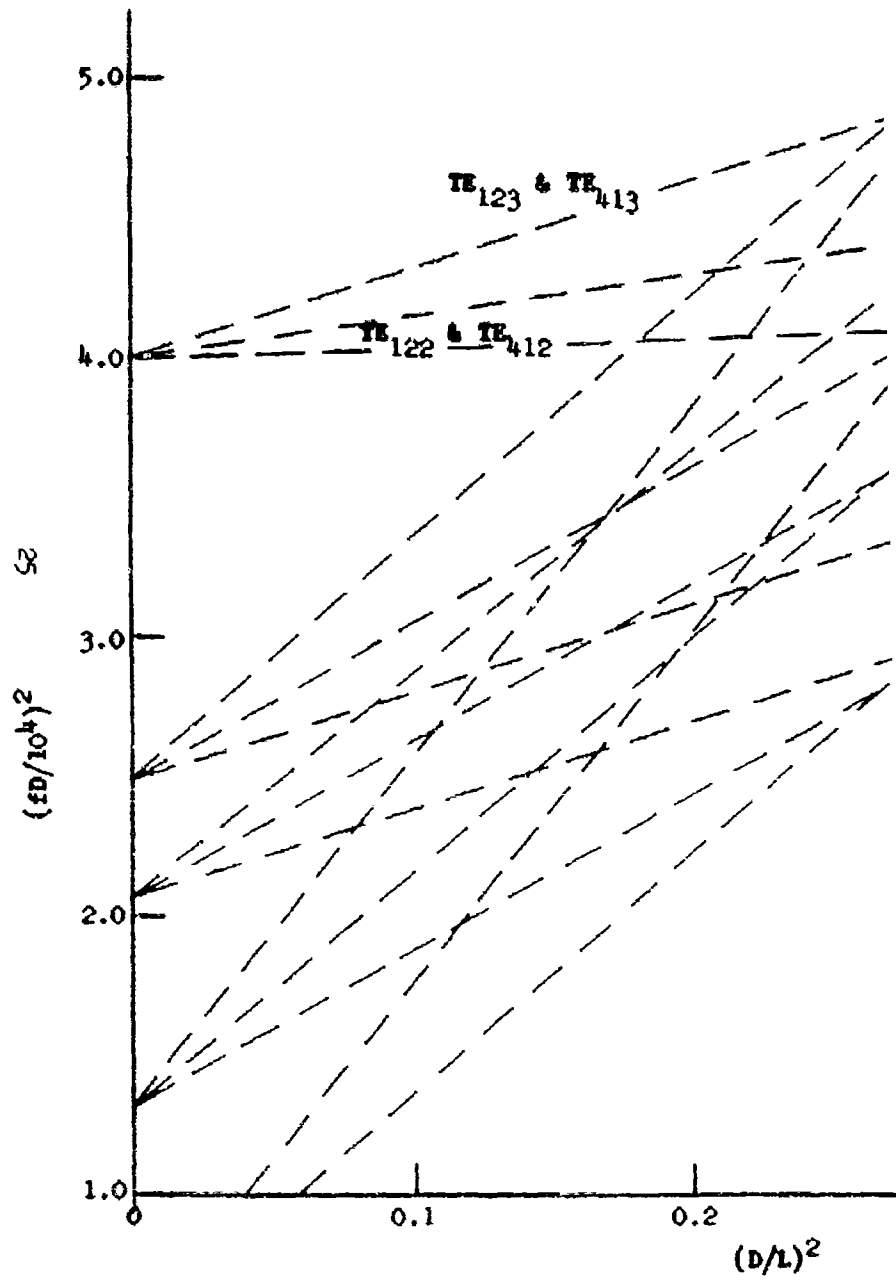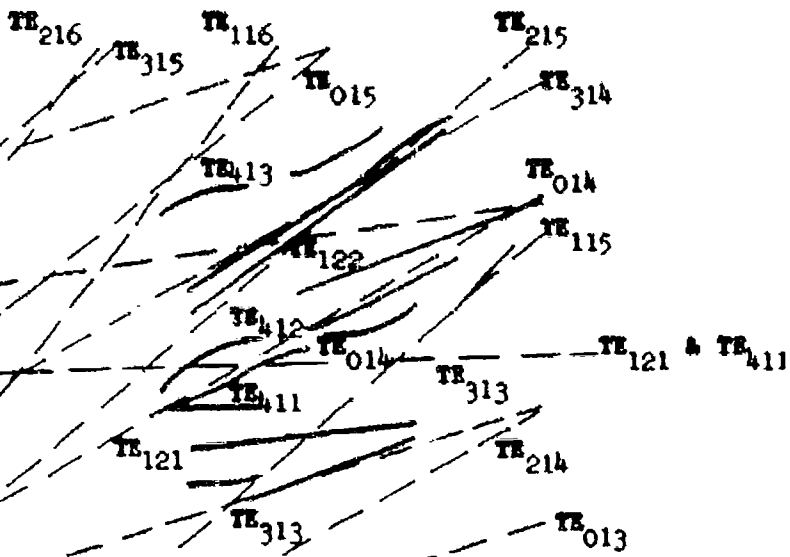Section A-A

FIGURE 11 CROSS-SECTION OF TE_{014} CAVITY COLD TESTER

FIGURE 12   TE$_{014}$ CAVITY

TE_{014} Cavity

$(D/L)^2 = 0.339$ $L = 0.980"$ $D = 0.570"$
(TE modes only)

— — — Theoretical modes
————— Actual modes
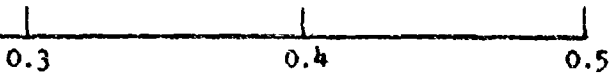
CAVITY MODE CHART

a narrow circumferential slot were cut in the cavity wall between the two vane resonant structures, it would intercept non-TE_{01n} mode currents but not TE_{01n} mode currents. In addition, if behind this circumferential slot suitable absorbing material were placed, all the non-TE_{01n} 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_{01n} modes had Q_u's too small to measure.

The suppression of the TE_{01n+1} and TE_{01n-1} modes is considerably more difficult to achieve because any of the absorption techniques that could be employed also affect the TE_{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_{014} mode at 35 Gc has been used to evaluate the mode suppression techniques. Since the single-stage TE_{012} mode tube (to be discussed later) operated satisfactorily with no tendencies toward operation in the TE_{011} or TE_{013} modes, it is apparent that a stabilizing disk is not required if the frequency of the interfering TE_{01n} mode is sufficiently removed from the operating frequency of the desired TE_{01n} mode. However in a TE_{014} mode cavity, the TE_{013} and TE_{015} modes, considered interfering modes, are much closer to the desired TE_{014} mode frequency than is the case for the shorter cavity length used in the TE_{012} mode tube. Figure 13 shows a cross-section of the TE_{014} mode cavity used. Also shown are the wall currents for the TE_{013} and TE_{014} modes.

The measured values of the frequency of the TE_{013}, TE_{014}, and TE_{015} modes along with measured values of Q_u are as follows:
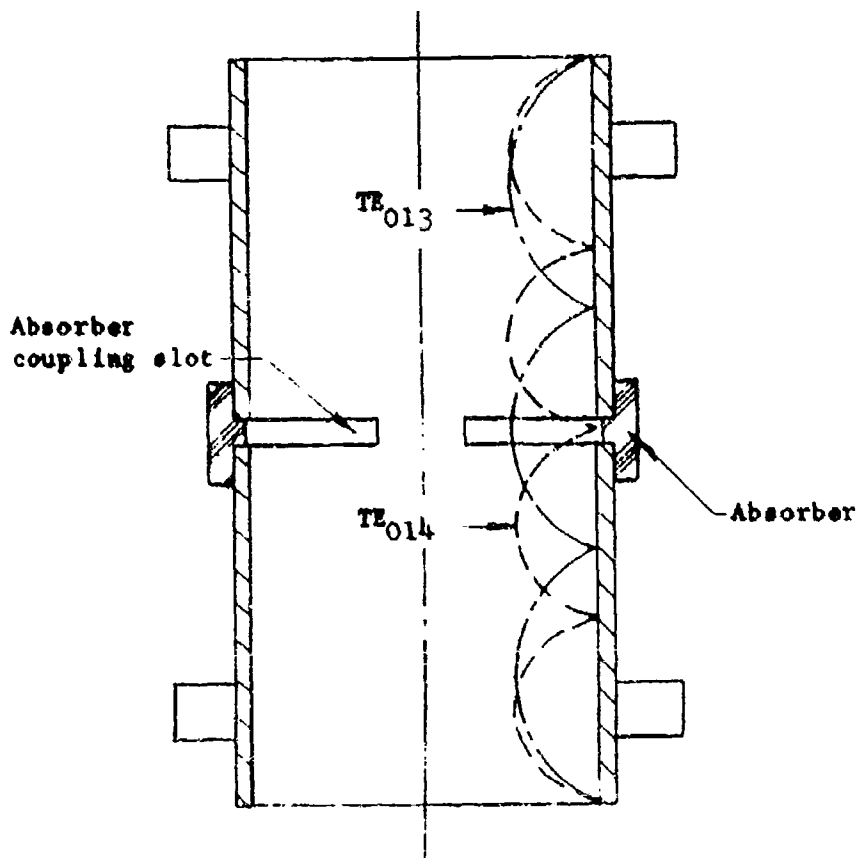
FIGURE 13   CROSS-SECTION OF TWO-STAGE ANODE SHOWING
AXIAL CURRENT DISTRIBUTION FOR THE TE_{013}
AND TE_{014} MODES

Mode	Frequency		Q_u
	Measured	Calculated	
TE_{013}	32.2 Gc	30.9 Gc	less than 1000
TE_{014} (desired)	34.7 Gc	34.7 Gc	5750
TE_{015}	38.2 Gc	39.1 Gc	4500

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.

Mode	Q_u		Percent decrease in Q_u
	With absorber	Without Absorber	with absorber
TE_{014}	5720	6650	14%
TE_{015}	1860	2435	23%

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 independent 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 now 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}
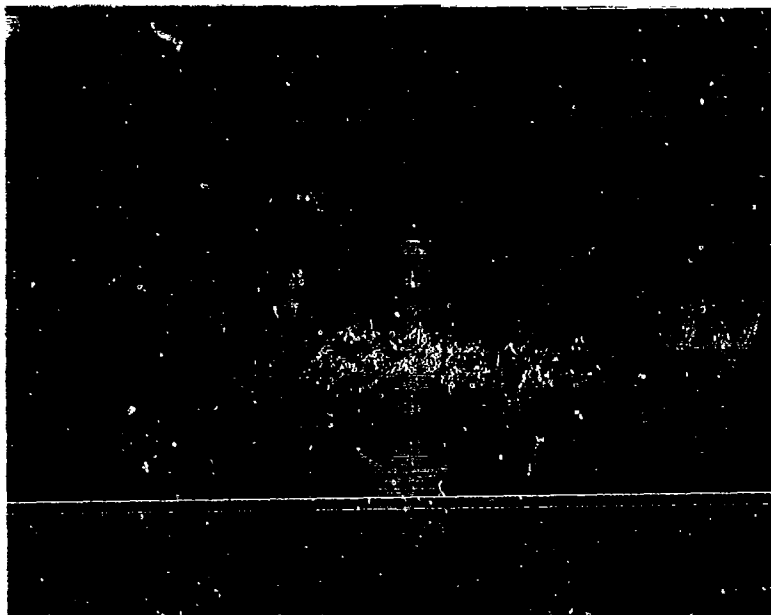
FIGURE 14   PHOTOGRAPH OF ONE-PIECE
             TWO-STAGE ANODE

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hybrid cold tester 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 · the tuning curve indicated that the desired coupling was obtained. Th. 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

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2. Cruft Laboratory Staff, Harvard University, ELECTRONIC CIRCUITS AND TUBES, McGraw-Hill Book Company, pp. 474-477, 496-499 (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 $k < 1/Q_2$ 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 $k < 1/Q_2$, $k = 1/Q_2$, and $k > 1/Q_2$.
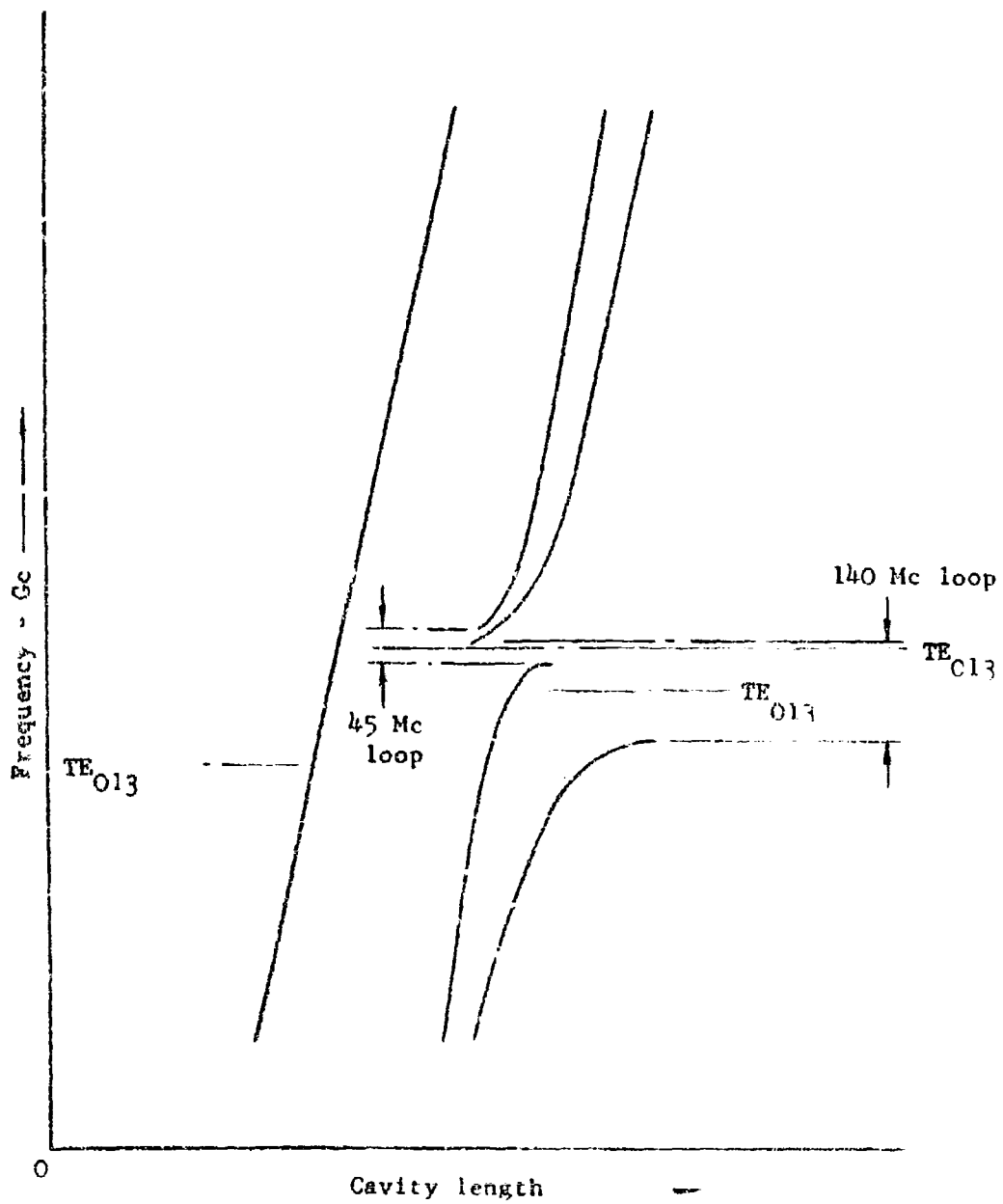
FIGURE 15   DRAG LOOP

5.0 OPERATING TESTS AND EVALUATIONS

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 Gc. 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 Gc to 35.95 Gc, a 3.75 Gc 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 Gc. This means that the cavity is now one half-wavelength instead of two half-wavelengths long.
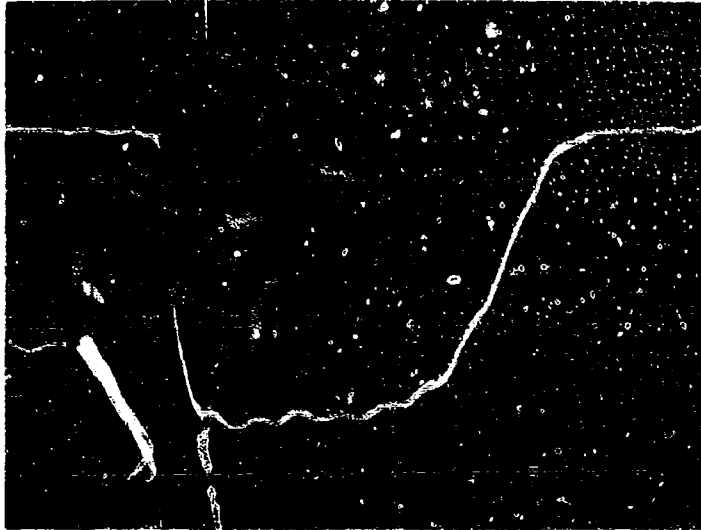
FIGURE 16   DETECTED RF OUTPUT PULSE OF FIRST HYBRID TUBE (F32D)
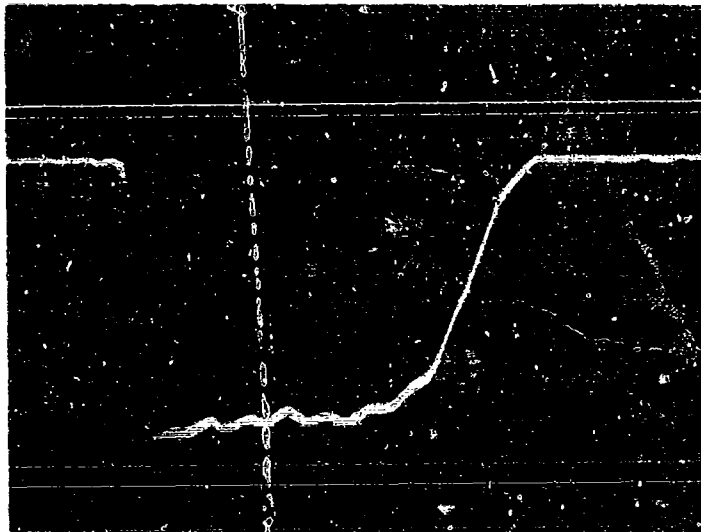OPERATING IN TE_{011} MODE AT 120 kw LEVEL

FIGURE 17   DETECTED RF OUTPUT PULSE FOR FIRST HYBRID TUBE (F32D)
OPERATING IN TE_{012} MODE AT 80 kw LEVEL

Under these conditions, the hybrid tube generated over 100 kw peak power
output with approximately 8 nsec RMS jitter. The results of this experi-
ment 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 TE_{012} and TE_{013} modes. Since the first
hybrid tube demonstrated that the starting jitter in the 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 TE_{012} cavity
mode (desired mode) at 34.4 Gc. The output power was 155 kw at an effi-
ciency of 21.4% and the starting jitter was low. Figure 18 is a photo-
graph of the detected RF pulse in the TE_{012} mode of operation. This
tube operated at nearly twice the power output level of the first hybrid
tube in the 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 TE_{012} cavity mode, could be tuned from
30.64 Gc to 34.92 Gc (a band of 4.28 Gc) with no mode competition from
adjacent TE_{01n} modes (TE_{011} and TE_{013}). However, if the tube was tuned
to frequencies lower than 30.9 Gc in the TE_{01} cavity mode oscillations
would cease at 30.64 Gc (TE_{012} mode) and shift to 34.8 Gc - the TE_{013}
cavity mode.

The second hybrid tube was then adjusted for TE_{013} cavity mode
operation at 34.5 Gc. The starting jitter in the TE_{013} mode of operation
was greater than that exhibited in the TE_{012} 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 19 shows the
detected RF pulse with the jitter clearly visible. Figure 20 shows
expanded sweep photographs for the purpose of jitter measurements. The
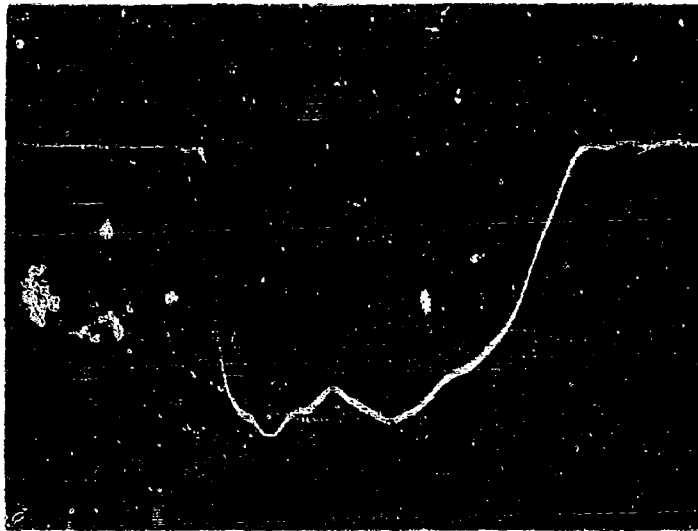
FIGURE 18   DETECTED RF OUTPUT PULSE OF SECOND HYBRID TUBE (16D)
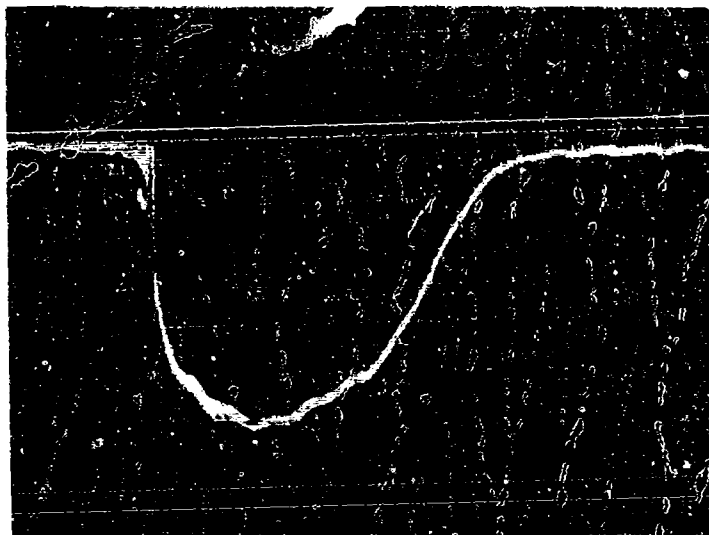OPERATING IN TE_{012} MODE AT 155 kw LEVEL

FIGURE 19   DETECTED RF OUTPUT PULSE OF SECOND HYBRID TUBE (16D)
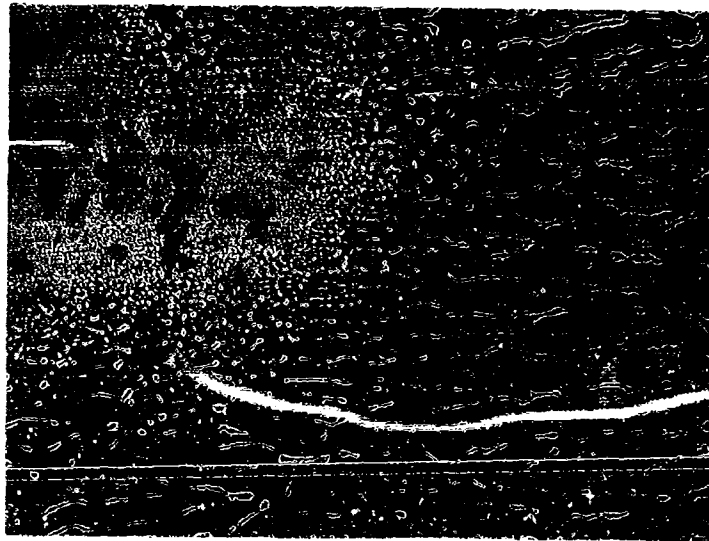OPERATING IN TE_{013} MODE AT 112 kw LEVEL

FIGURE 20   DETECTED RF OUTPUT PULSE OF SECOND HYBRID
TUBE (16D) SHOWING PEAK-TO-PEAK STARTING
JITTER IN TE_{013} 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 sy em. 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 near disappeared when the tunable section was shifted in frequency way 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 100 kw at 0.45 μsec and 0.00023 duty cycle. The tunable section contributed

FIGURE 21   PHOTOGRAPH OF TWO-STAGE ANODE SUB-ASSEMBLY

FIGURE 22   PHOTOGRAPH OF FIRST TWO-STAGE TUBE (J25D)

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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, AI-E, which was completed for evaluation in January 1967, initially showed greater than normal amounts
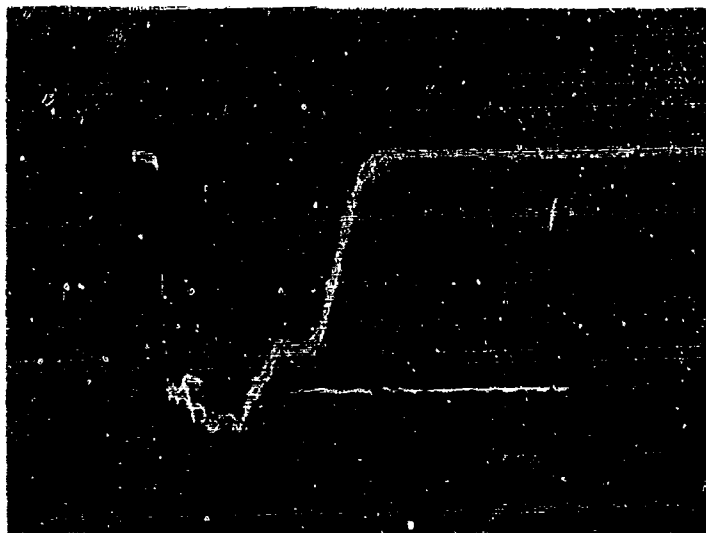
FIGURE 23   DETECTED RF OUTPUT PULSE OF FIRST TWO-STAGE TUBE (J25D)
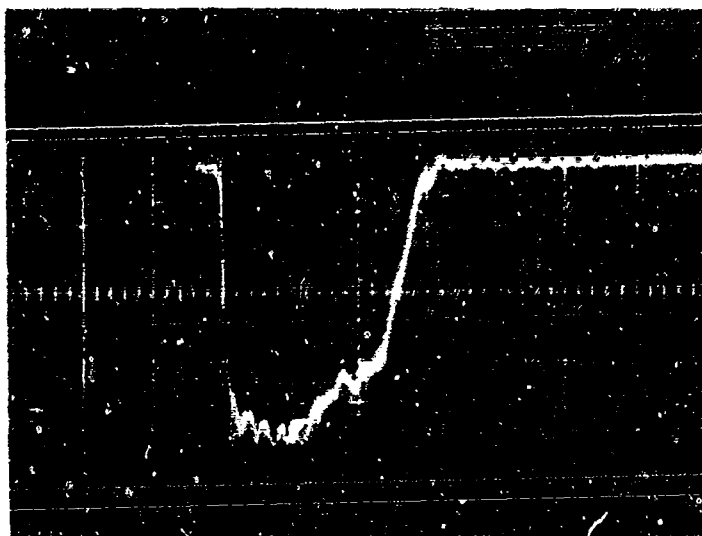   WITH ONLY TUNABLE SECTION BEING PULSED

FIGURE 24   DETECTED RF OUTPUT PULSE OF FIRST TWO-STAGE TUBE (J25D)
             WITH BOTH SECTIONS OPERATING

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of starting jitter when seasoning was attempted. This tube incorporated
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
is designed to inhibit non-TE_{0ln} cavity modes. Since the first two-stage
tube (J25D) exhibited no apparent non-TF_{0ln} mode contamination, the
exclusion of this absorber seemed possible. To help offset the lack of
non-TE_{0ln} 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 evalua-
tion 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 1.5 kw and no

measurable starting jitter was encountered. When the tunable section (TE_{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 55% of the total power output was derived from the output section of the tube. This test was performed at a low output level (~ 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.
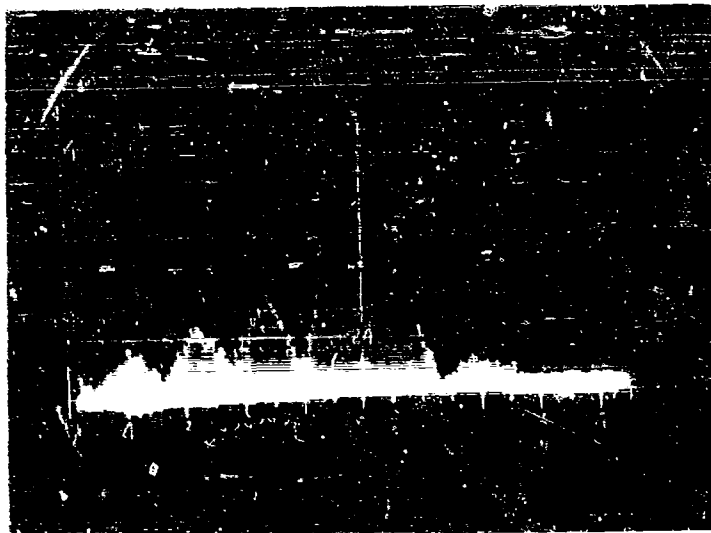
FIGURE 25   SPECTRUM DISPLAY OF TUBE J25D-R WITH
             BOTH SECTIONS OPERATING

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6.0 TEST EQUIPMENT

6.1 Q Measuring Equipment

The TE_{01} circular waveguide size used in the Ka-band ICEM 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 WC59 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 26 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.

6.2 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.

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3. E. D. Reed, "A Sweep Frequency Method of Q Measurement for Single-ended Resonators," Proc. of the National Electronics Conference, Vol. 7, pp. 162-172, 1951
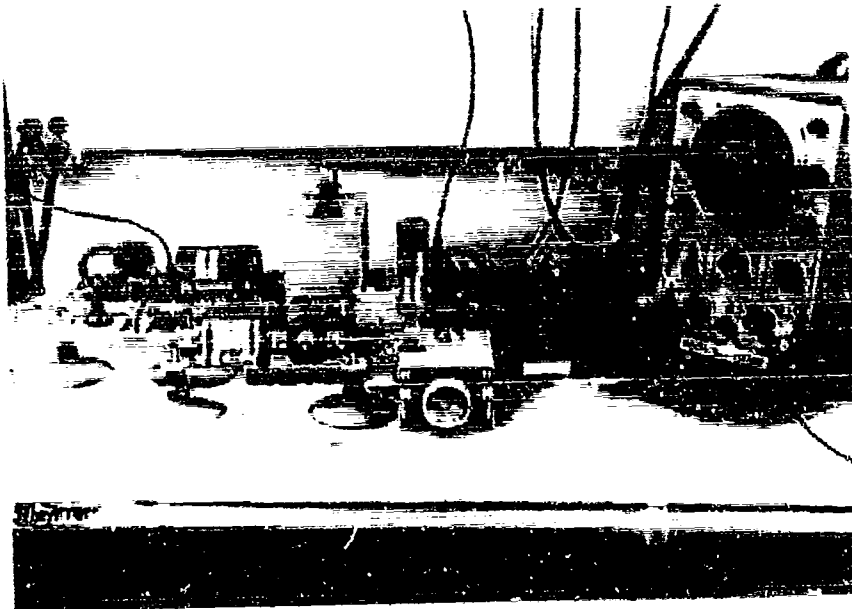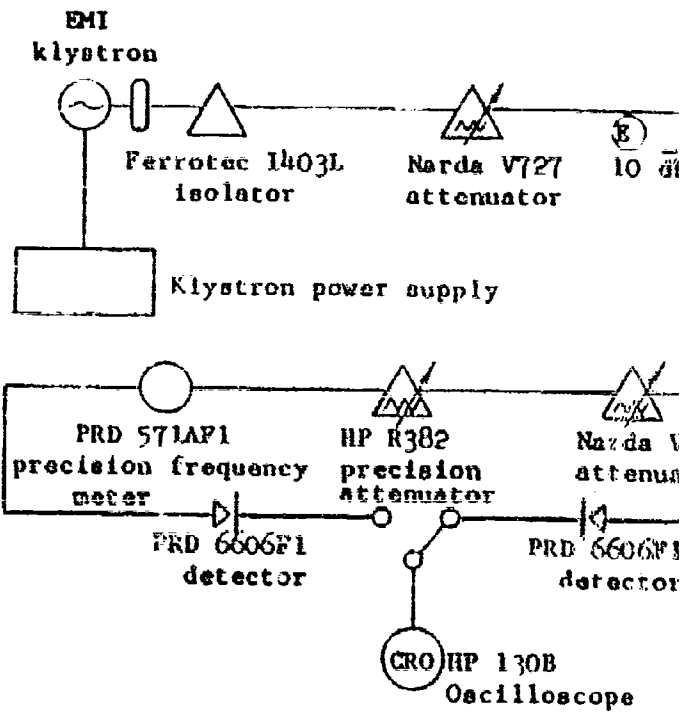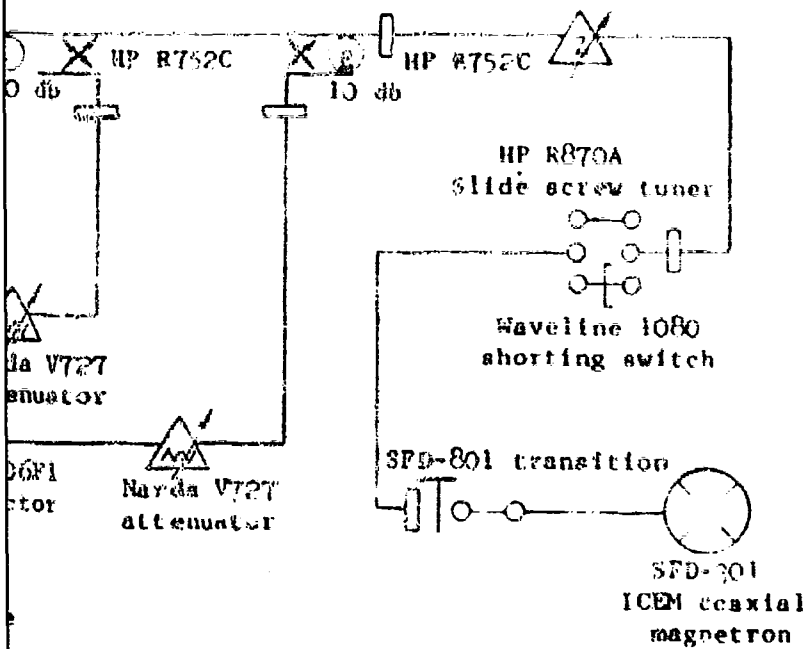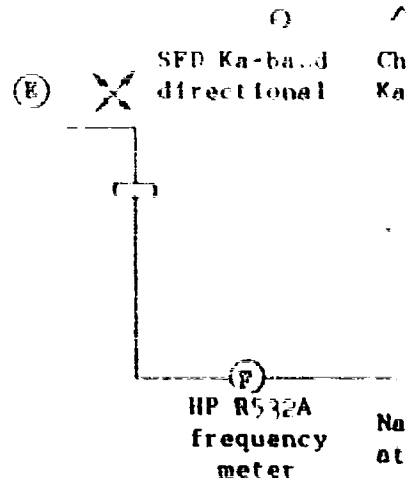
FIGURE 26   PHOTOGRAPH OF Ka-BAND Q MEASURING TEST SET

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EMI
klystron

Ferrotec 1403L
isolator

Narda V727
attenuator

10 dB

Klystron power supply

PRD 571AP1
precision frequency
meter

HP R382
precision
attenuator

Narda V
attenua

PRD 6606F1
detector

PRD 6606F
detector

CRO HP 130B
Oscilloscope

FIGURE 27   SCHEMATIC OF Ka-BAND

HP R752C   HP R752C

0 db   10 db

HP R870A
Slide screw tuner

Narda V727
attenuator

Waveline 1080
shorting switch

Narda V727
attenuator

SFD-801 transition

SFD-301
ICEM coaxial
magnetron

AND Q MEASURING TEST SET

ICEM coaxial magnetron

SFD Ka-band   Ch
(E)   ✕   directional   Ka

HP R532A
frequency   Na
meter   at

51

FIGURE 26   SCHEMATIC OF Ka-BAND TUBE

Chemalloy
Ka-band

Chemalloy SME-10;
calorimeter

Spectrum analyzer

Narda V727
attenuator

PRD 660FP1
detector

CRO

Tektronix 541
oscilloscope

UBE TEST SET

S·F·D laboratories, inc.

A directional coupler was designed to couple power from the TE_{01} 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 strapping 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 P_b factor of the thyratron 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.

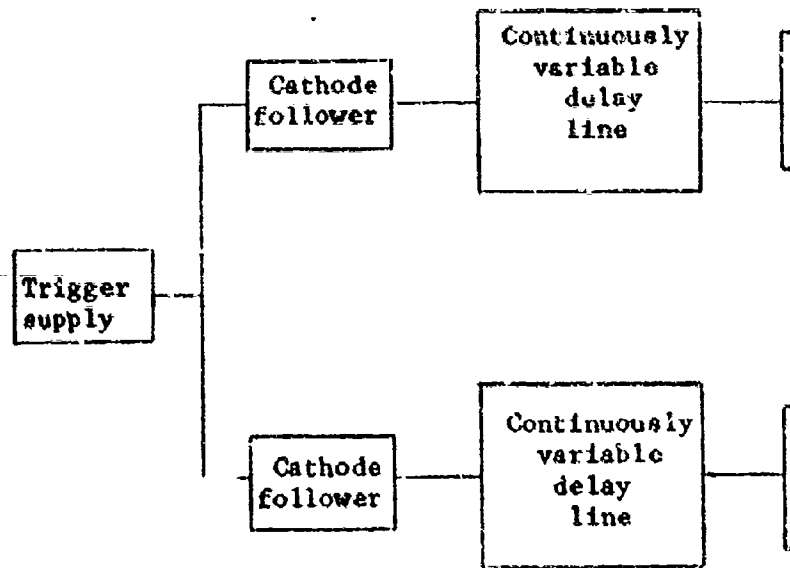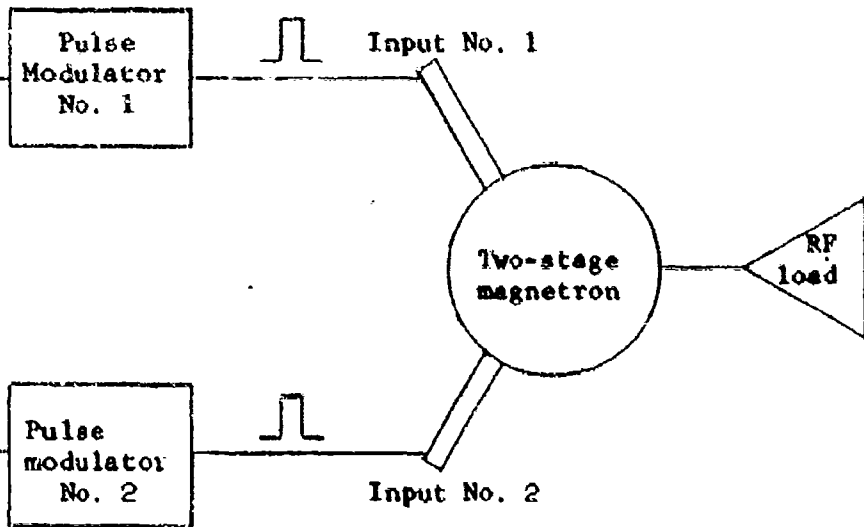FIGURE 29 BLOCK DIAGRAM SHOWING SYNCHRO

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 o. 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 mag..etron. The output or amp'ifier section, however, is a relatively new conce, 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 Gc and above.