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Research and Development Technical Report

ECOM-0226-F

TRANSVERSE-WAVE HIGH-POWER TUBE

FINAL REPORT

By

C. BURTON CRUMLY

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TECHNICAL REPORT ECOM-0226-F June 1968

TRANSVERSE-WAVE HIGH-POWER TUBE

FINAL REPORT

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U. S. Army Electronics Command, Fort Monmouth, N. J. 07703

ABSTRACT

Research and development work is described on a power amplifier tube employing transverse-wave interaction between the negative synchronous wave and a traveling circuit wave on a balanced structure. The theoretical advantage in this arrangement is the possibility of high-power amplification with high overall efficiency, due to the lack of longitudinal or transverse velocity modulation in the spent beam.

The initial design parameters are reviewed, and modifications are discussed. The design and fabrication of the attenuator is outlined, and measured results presented. Modifications to the waveguide input and output sections, and to the vacuum windows, are described.

Consideration was given to a possible extension of the design to X-band at higher powers, although no firm extrapolation could be made at the present time.

Assembly and processing of the first complete tube is described, along with the difficulties encountered. Testing of the tube showed that the dc behavior was reasonably satisfactory, but the rf behavior was not as expected. The search for synchronous-wave interaction is outlined; while some indirect evidence of a transverse interaction was believed to have been observed, it was not possible to identify positively the desired amplification mode. The reasons for this failure are thought to be associated with the particular circuit employed, although no specific reason could be found.

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1. PURPOSE

The purpose of this program has been to conduct research and development of a theoretical and experimental nature, on a transverse-wave high-power amplifier tube in accordance with U. S. Army Electronics Command, Electron Tubes Division Technical Guideline No. MW-52A dated 28 June 1966, entitled "Cyclotron and Synchronous Wave Devices Investigation."

The primary task of this program was to complete and test an experimental model to confirm the feasibility of the device and to demonstrate its ability to meet the performance goals. These objectives were: 1 kw of RF power at a depressed-collector efficiency of at least 60% and with at least 20 db saturated gain at S-band.

The feasibility of extending the design to X-band at a 10-kw level was also to be considered.

2. BACKGROUND AND SYNOPSIS

Previous theoretical and experimental work conducted under contract DA28-043 AMC-01268(E) accomplished the development of a twisted, finned, ridged, circular waveguide tube circuit. Experimental information showed that an appropriate dispersion curve, as well as adequate interaction impedance could be obtained at S-band. A completed RF circuit including all necessary transitions and input and output RF windows yielded broadband coupling from 3.5 to 4.6 gHz.

Gain theory indicated that spurious coupling to the fast cyclotron wave was negligible. This theory also predicted that the electron velocity could vary as much as ±7% before the gain would drop by as much as 20% of the synchronous gain in db.

A circuit impedance of 330 ohms was experimentally determined. The resulting gain constant, which was calculated to be about 7.8 db per inch, was expected to be reduced by transverse field variations across the gap, energy carried in higher-order space harmonic fields, and circuit losses.

The design of the prototype tube was completed and most of its integral parts were fabricated at the end of the contract period, 30 June 1966.

Work began on the present contract on 1 January 1967, to complete the experimental tube fabrication and testing. During the first quarter, all aspects of the basic design were reviewed. While the circuit velocity and impedance appeared to be satisfactory, the clearance for the beam was found to be inadequate for the desired 1 kw power level, particularly when account was taken of the actual beam size produced by the guns tested in the previous program. Since the gap could not be widened without adversely changing the circuit velocity and impedance, it was decided to proceed with the circuit on hand, even though the maximum power would probably be limited to about 200 watts.

The attenuator design and fabrication were completed during the first quarter. The method employed was that of pyrolytic deposition of carbon in a porous ceramic, from a methane atmosphere. The resistivity obtained was adequate to yield sufficient attenuation in the actual circuit, to insure tube stability over the band with 25-30 db net gain; tapers into and out of the attenuator were included to minimize spurious reflections at these points.

Circuit assembly and processing jigs were completed, and assembly of gun and collector sections was begun.

The second quarter was devoted largely to the solution of fabrication problems in the waveguide input and output sections, and correction of a faulty vacuum window configuration. A brazed assembly of stainless steel was substituted for the electroformed waveguide sections, and the ceramic window design was modified to allow for complete circumferential heliarc welding.

Preliminary calculations of a possible X-band tube were also done during the second quarter, although no circuit models were constructed for cold testing, due to the priority of work on the S-band tube. The preliminary indications were that a suitable configuration could probably be found, and that gun requirements would be reasonable. However, until cold tests could be performed on an actual circuit to determine phase velocity, these preliminary results could not be confirmed quantitatively.

Work during the third quarter was devoted entirely to final assembly and processing of the S-band tube. Major difficulties were encountered with the vacuum windows, and further design modifications were required to obtain a tight seal. No problems arose in stacking and sintering the rf circuit assembly or in heliarc sealing the joints, other than the windows. Processing the tube on the pump was accomplished in about one week, but this had to be repeated due to development of two leaks. Because of a tool malfunction, the tube went down to air at tip off; the tubulation was then replaced and the tube reprocessed. The subsequent processing cycle was completely successful, and testing began in October.

In the fourth and final quarter, tests were performed on the tube in the solenoid, first with low-voltage continuous dc, and later with pulsed voltages up to about 16 kv. During these tests, the appendage pump was able to handle all outgassing, and the pump current was continuously monitored, so as to avoid pressures high enough to damage the cathode emission. The dc behavior of the tube appeared to be satisfactory, at least insofar as measured beam current, perveance, interception, and collector current were concerned. However, the rf performance was not as expected; the synchronous-wave interaction, for which the tube was designed, could not be positively identified. These tests are outlined in detail below.

3. SUMMARY OF INITIAL DESIGN PARAMETERS

For reference purposes, this section summarizes the important design parameters for the tube at the beginning of the present program; further details and supporting data can be found by referring to the reports on the previous contract.

Since the traveling-wave circuit is the heart of the device, its characteristics were the determining factors for the choice of the operating parameters for the tube. These parameters, such as beam voltage and current, center frequency and passband, magnetic field, etc., were chosen to be consistent with the actual measured characteristics of the circuit as constructed, including the transition sections, vacuum windows, and attenuator.

The active section of the rf circuit was 14.7" long, composed of alternating fins and spacers each of thickness 0.020", yielding a fin-to-fin spacing of 0.040". The twist consisted of a 10° rotation between adjacent fins, such that a full twist cycle contained 36 fins and 36 spacers, with a full twist pitch distance of 1.440" or 3.658 cm. The transverse gap spacing was 0.100". The measured phase velocity of this structure, taking into account the twist, was 19.2% of light velocity at 4.1 gHz, corresponding to a beam voltage of 9.46 kv.

While the exact value of the magnetic field is not critical to the interaction process, the design value was taken such that the cyclotron frequency was 4.1 gHz, or a field of 1,460 gauss. The electron gun selected for this tube had a perveance of 0.5 x 10^{-6} amp/(volt)$^{3/2}$, yielding an operating beam current of 0.460 amp at 9.46 kv, and a dc beam power of 4.35 kw.

The transmission-line impedance of the circuit was expected to be 300-400 ohms in the tube operating band (3.5-4.6 gHz), on the basis of perturbation measurements. The resulting theoretical gain constant, neglecting the impedance (and gain) reduction factors due to gap field variations, space harmonics, circuit attenuation, etc., was computed to be over 7 db per inch of active circuit length.

4. INITIAL DESIGN MODIFICATIONS

At the beginning of the present program all aspects of the design were reviewed, especially those concerning the amount of rf power that can be produced before saturation occurs.

The amount of available rf power in the beam is related to the transverse position of the beam by the following equation:

$$P_{rf} = \frac{I_o \omega . \omega_c b^2}{2\eta} \tag{1}$$

I_o is the beam current, ω is the operating radian frequency and ω_c is the cyclotron radian frequency, η is the electron charge-to-mass ratio and b is the radius of the synchronous-wave motion, which is limited by the distance between the edge of the beam and the nearest point of interception.

Since the beam produced by the electron gun was supposed to be 0.045 inch in diameter and the circuit gap was 0.100 inch, the maximum transverse movement would be 0.027 inch. For a beam current of 0.5 ampere and $f = f_c = 4.1$ gHz, the saturated power of the first tube would be a little over 400 watts. Based on previous experience it was expected that the beam might be some 30% larger than that predicted by the gun manufacturer. If this proved to be the case, the RF power output demonstrated by the first tube would be around 200 watts.

Serious consideration was given to widening the gap in the last two or three periods of the active circuit sections of the tube. However, it was decided that this would add too much uncertainty to the experimental information to be obtained about the interaction process. Also, as shown by Fig. 1, the required beam voltage would be much higher. As a consequence, it was decided to leave the circuit alone and correct for power handling in a subsequent model, after beam and circuit interaction were confirmed and understood.

The gun design was reviewed in order to confirm that the added focusing electrodes would be sufficient to provide extra control of the beam. At a cyclotron frequency of 4.1 gHz, the cyclotron wavelength is about 1.4 cm. The scallop wavelength should be several times larger than this value, depending upon the conditions at entrance to the magnetic field, amount of ripple, beam forming conditions, etc. There was sufficient space for focusing electrodes which would exert control on the beam for about one full cyclotron wavelength beyond the theoretical minimum-diameter point; more length could be provided if necessary in a later version.

The circuit length was increased by 1/2 a period. This was done to provide added gain and also to allow the tube to be the correct length for the solenoid, approximately 25 inches.

5. ATTENUATOR FABRICATION AND TESTS

The basic form of the attenuator is a thin ceramic ring which has been impregnated with carbon. Figure 2 shows the form of the

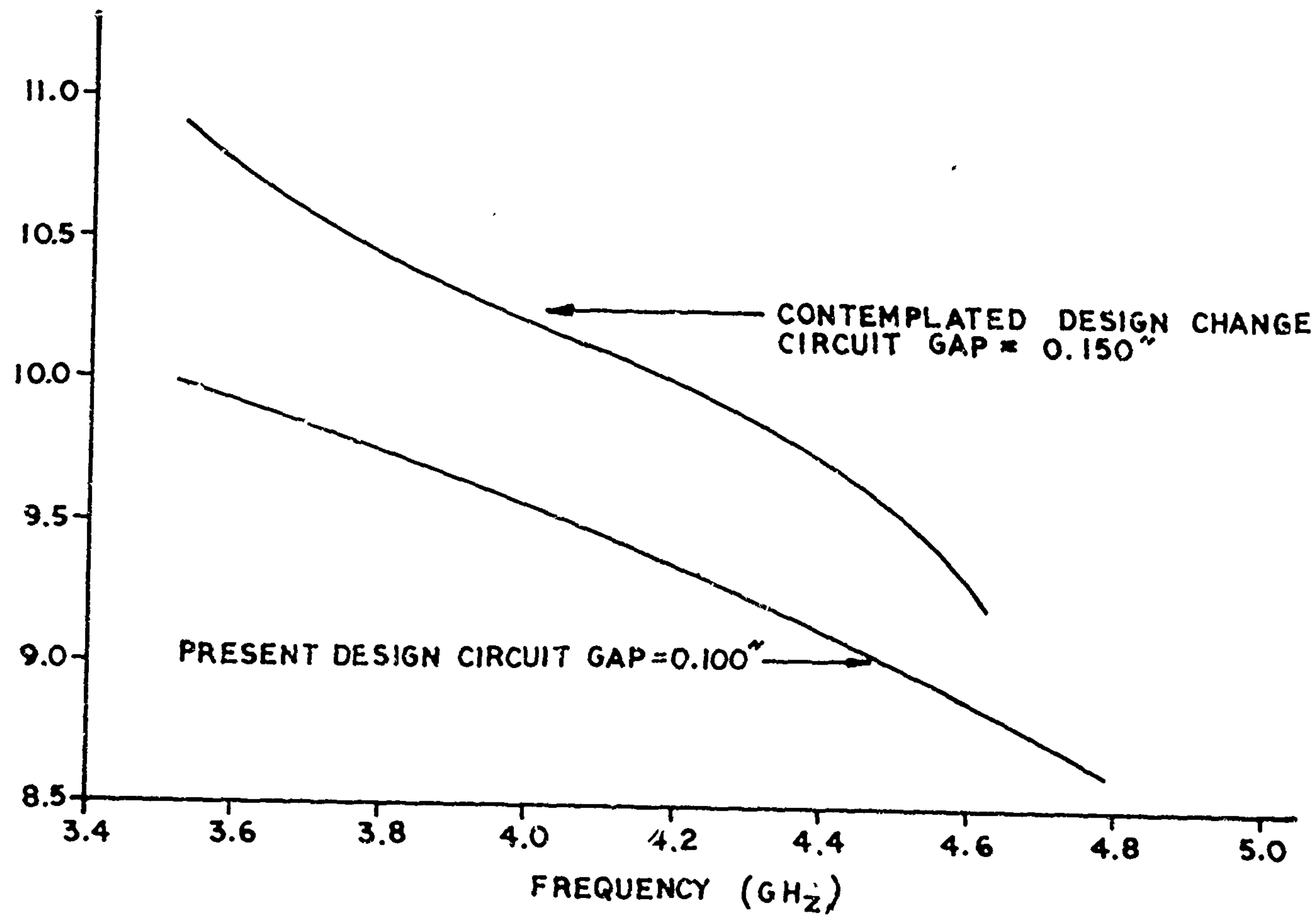


Fig. 1--Synchronous voltage as a function of frequency.

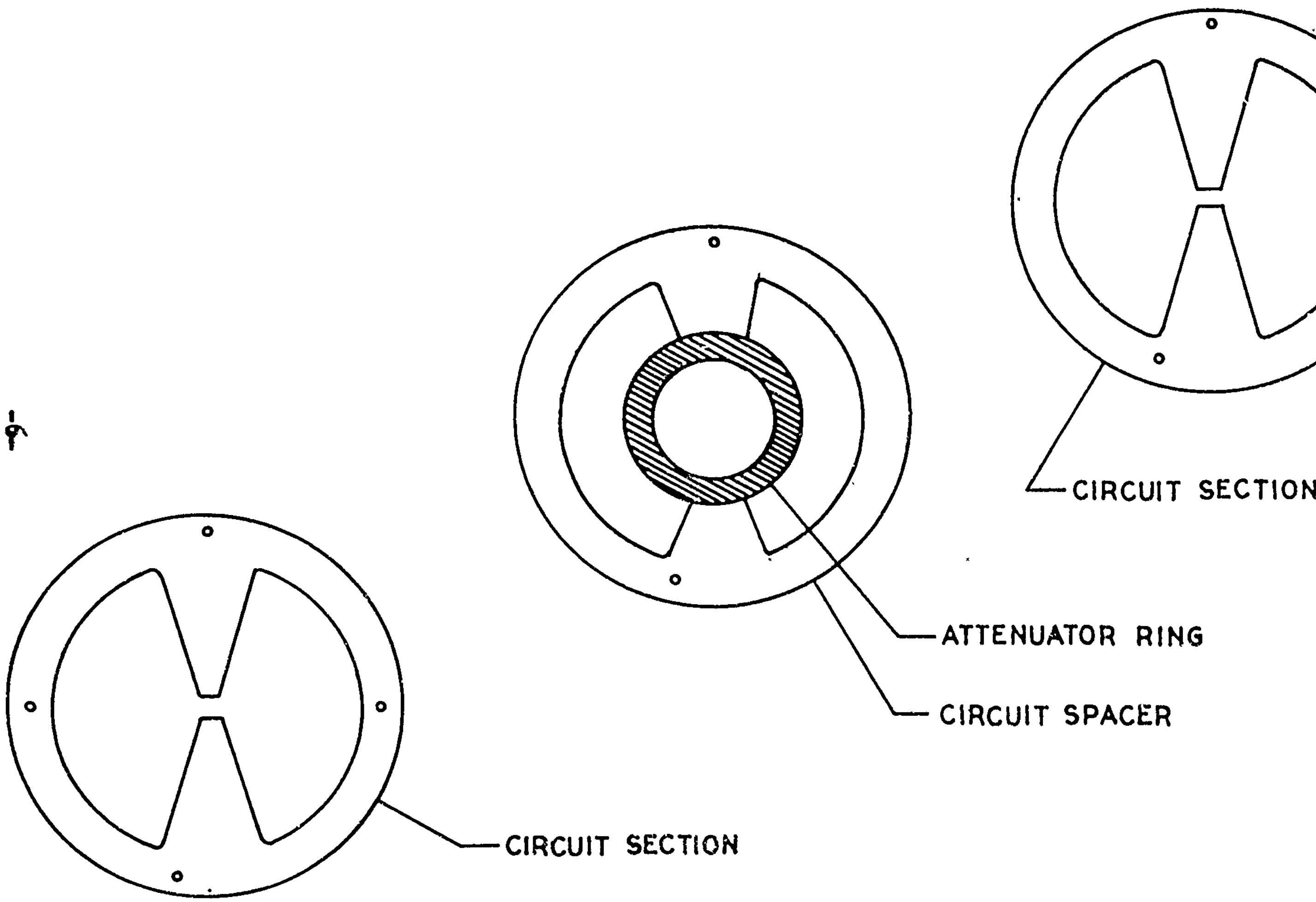


Fig. 2--Attenuator assembly.

attenuator assembly.

Its use as an integral part of the power tube RF structure necessitated the development of techniques and materials to meet unique electrical and mechanical requirements. These elements were to exhibit stable resistive values over a wide operating range and provide the necessary RF isolation from the output to the input of the RF structure.

Once the mechanical design of the needed elements was completed, a method or technique for providing the proper resistivity value was undertaken.

The technique of pyrolytic deposition of carbon on ceramic and sapphire substrates has been widely used in the microwave tube field for many years, especially in the manufacture of traveling-wave tubes. As a result, several techniques have been developed for carbon deposition. Of these various techniques, the cracking of a gas, such as methane, acetylene or benzene and depositing the free carbon atom on a porous ceramic, best suited our requirements. Also, by using a porous ceramic, it was possible to permeate the material with carbon. Methane was selected, and the technique was developed to fabricate the lossy discs of the desired resistivity.

After fabrication, the discs were evaluated by measurements of the attenuator in the actual RF circuit. This was carried out by making insertion loss and VSWR measurements for the combination of the attenuator rings shown in Fig. 3.

Attenuation data as a function of frequency are shown in Fig. 4 and 5. Typical VSWR measurements are shown in Fig. 6.

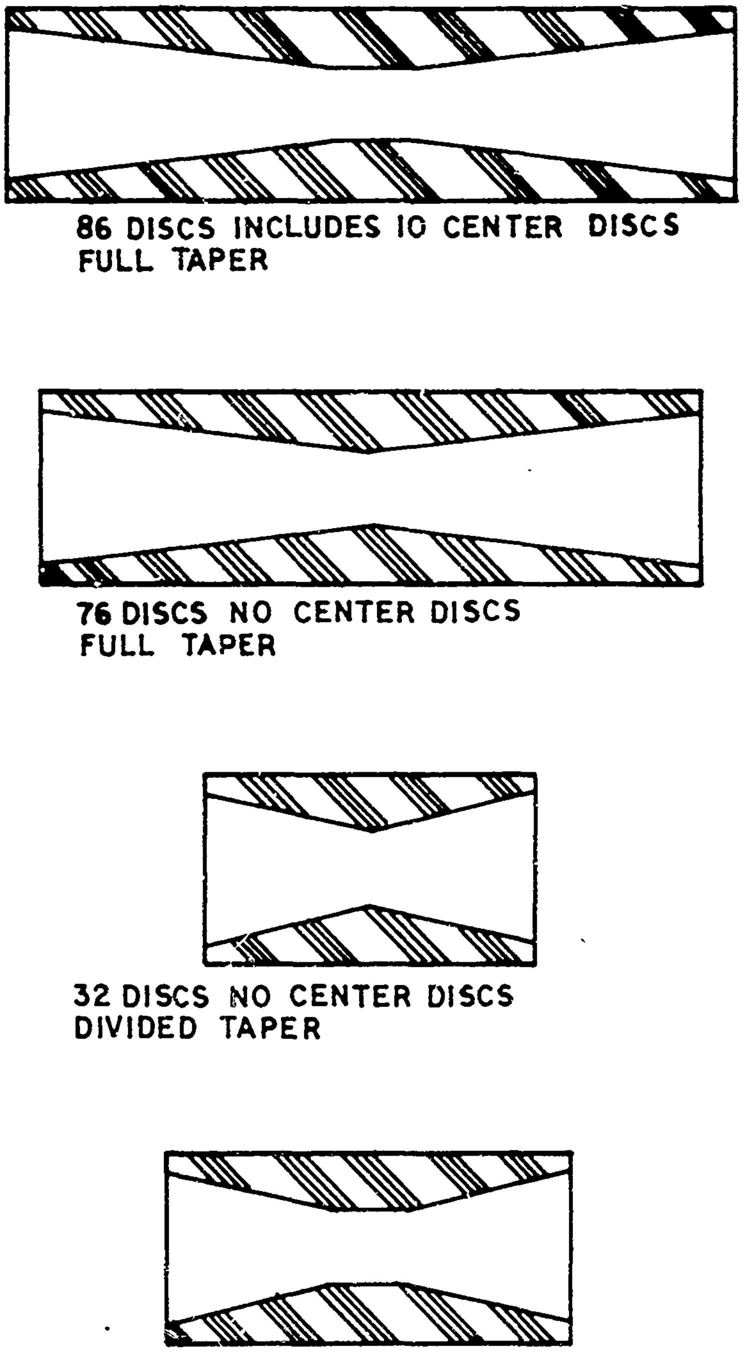
The experimental results confirm that it will be possible to obtain sufficient attenuation to insure tube stability.

6. WAVEGUIDE SECTIONS AND VACUUM WINDOWS

Pre-assembly tests were conducted on the electro-formed copper waveguide sections. It was determined that these sections were not strong enough to form a rigid air-vacuum interface. It was necessary to change the design to a brazed assembly of stainless steel. See Fig. 7.

At the pre-assembly stage, it was discovered that the window housing would not maintain a vacuum and it was necessary to change the configuration to that shown in Fig. 8. This structure now allows for complete circumferential heliarc welding; Fig. 9 shows a window and frame.

It was also necessary to make some minor changes in mating



86 DISCS INCLUDES 10 CENTER DISCS
FULL TAPER

76 DISCS NO CENTER DISCS
FULL TAPER

32 DISCS NO CENTER DISCS
DIVIDED TAPER

32 DISCS INCLUDES 10 CENTER DISCS
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Fig. 3--Attenuator forms used in the evaluation tests.

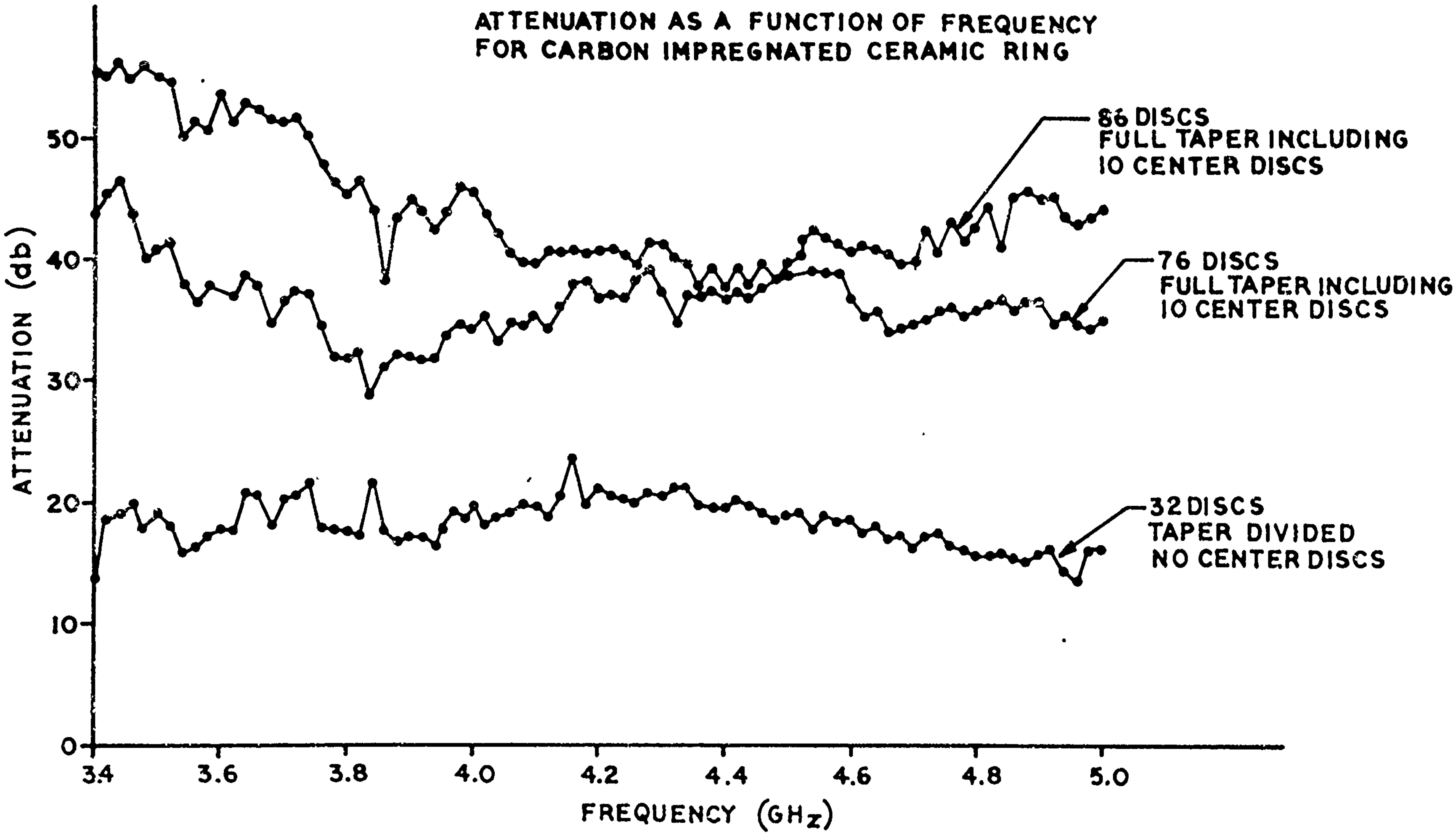

Fig. 4--Attenuator test results.

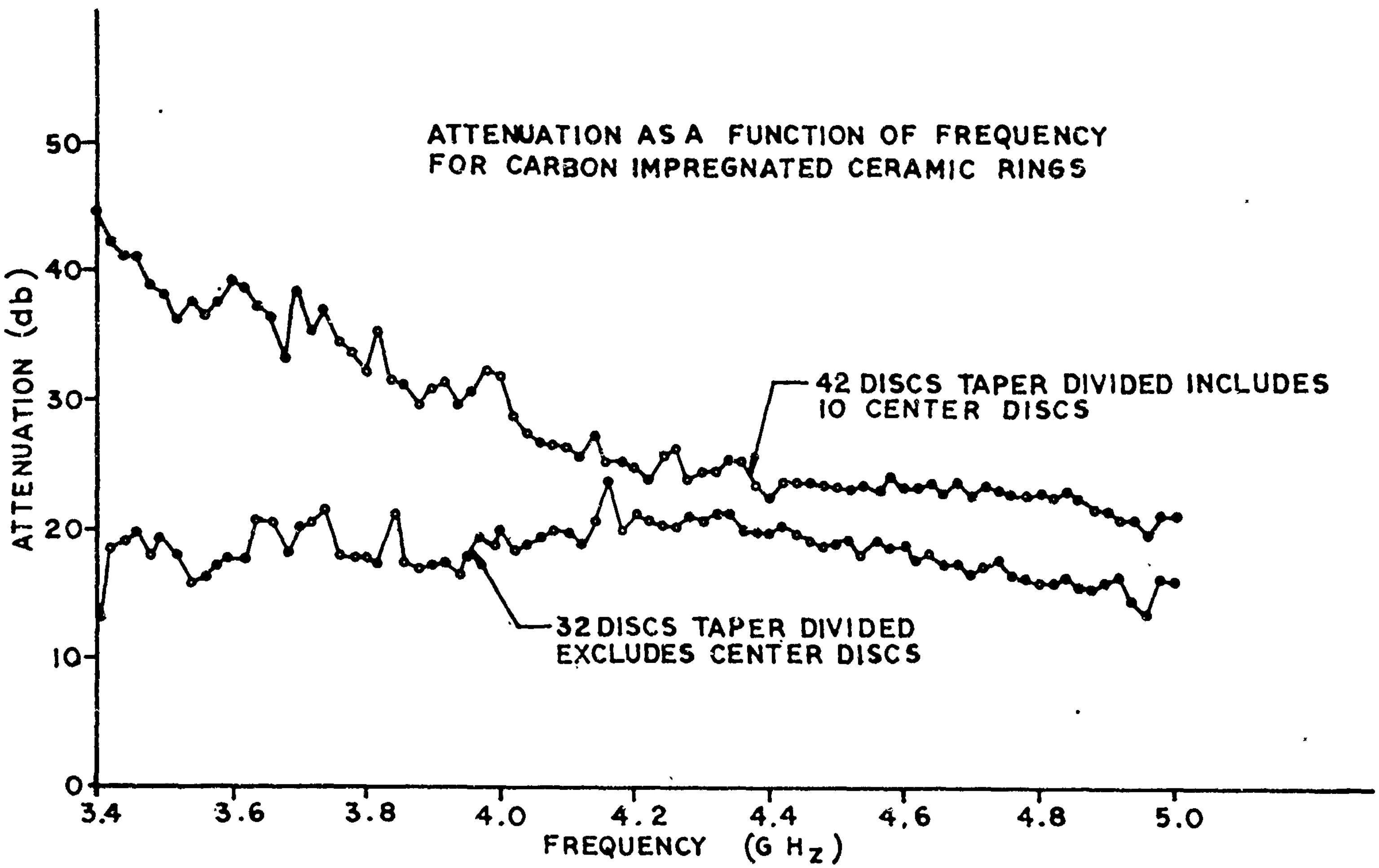

Fig. 5--Attenuator test results.

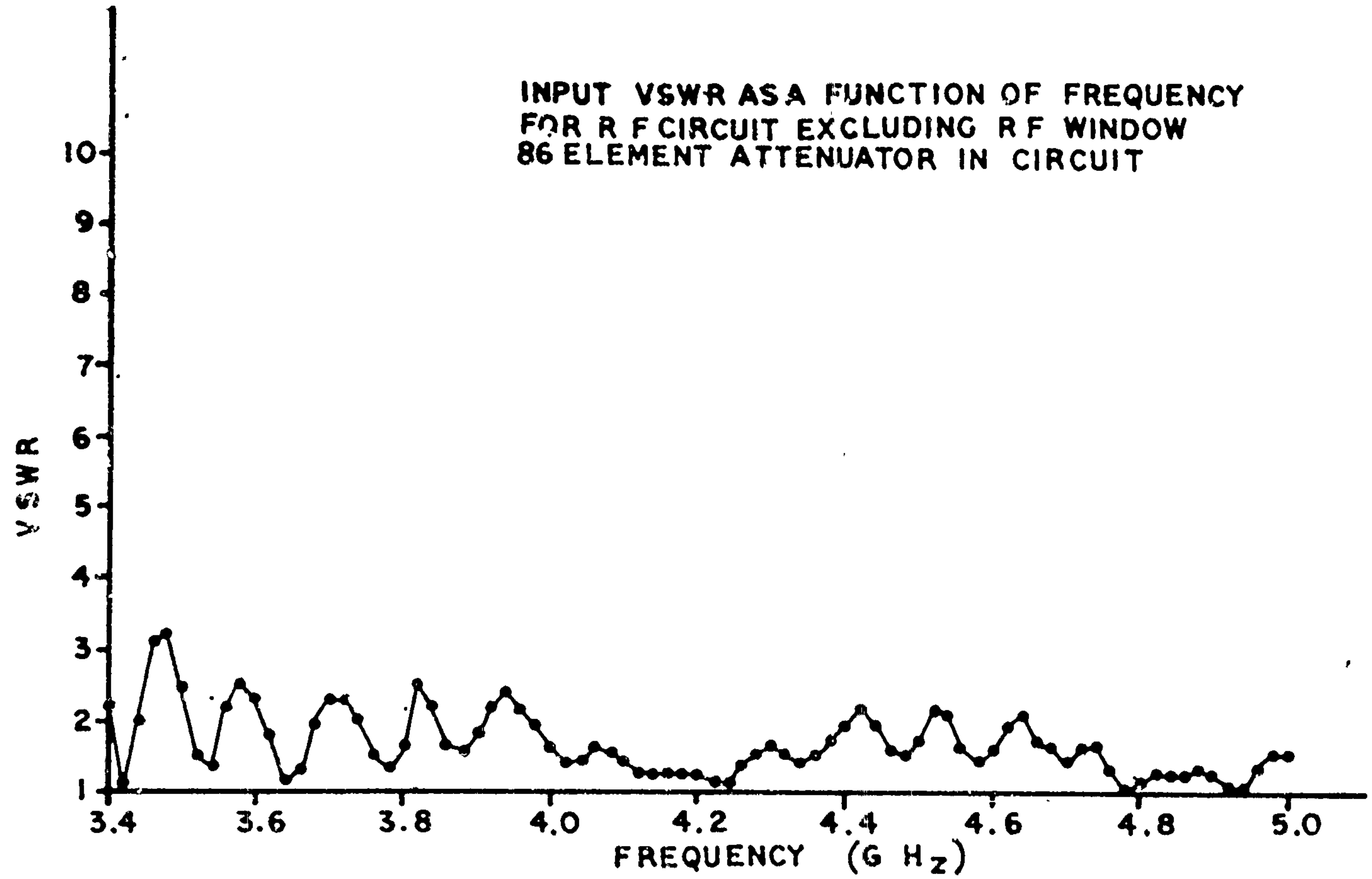

Fig. 6--Attenuator test results.

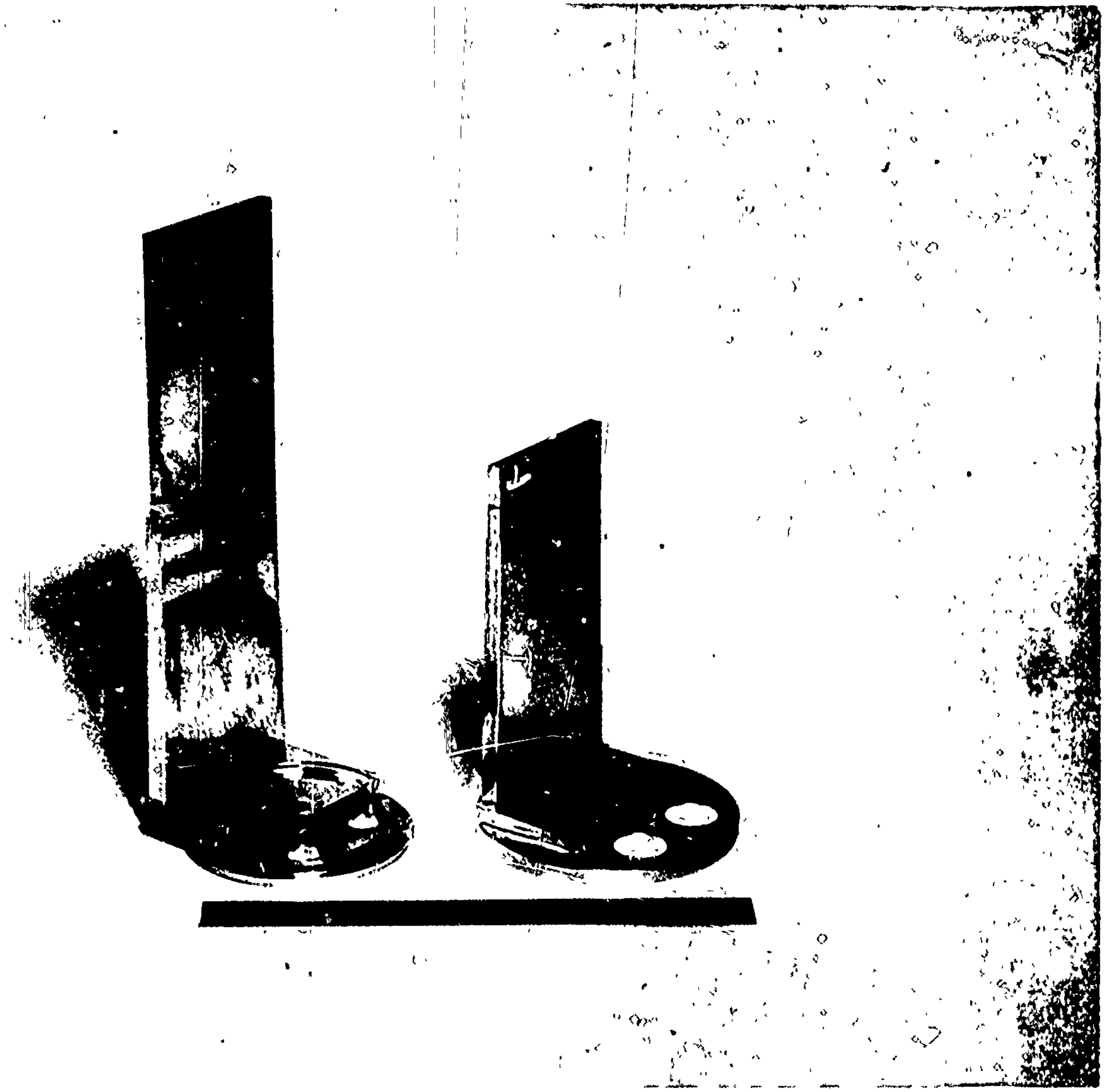

Fig. 7--Input and output waveguide assemblies.

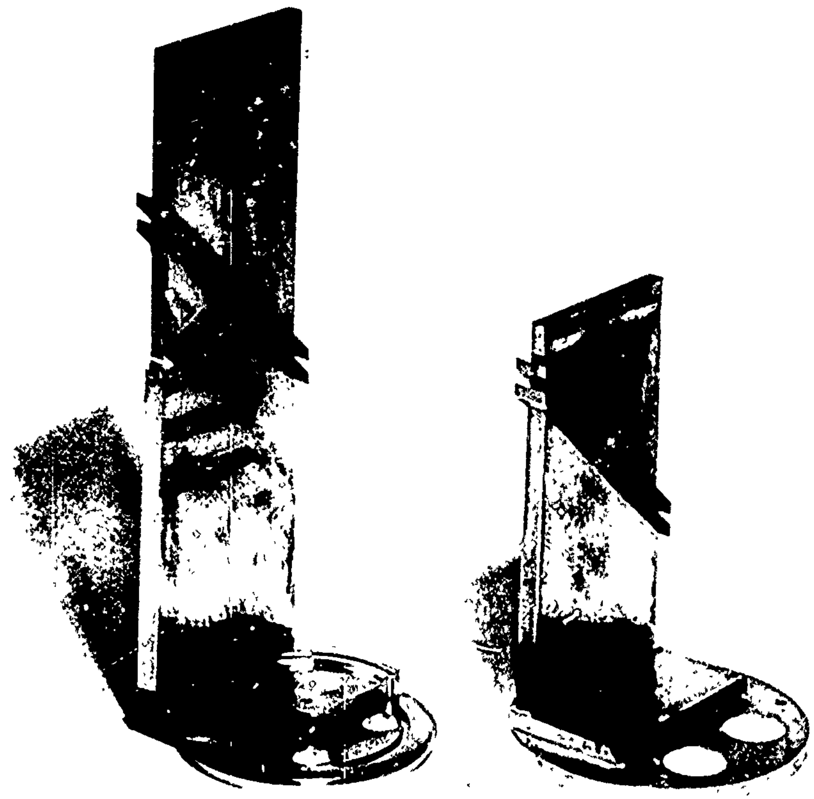

Fig. 8--Input and output waveguide assemblies.

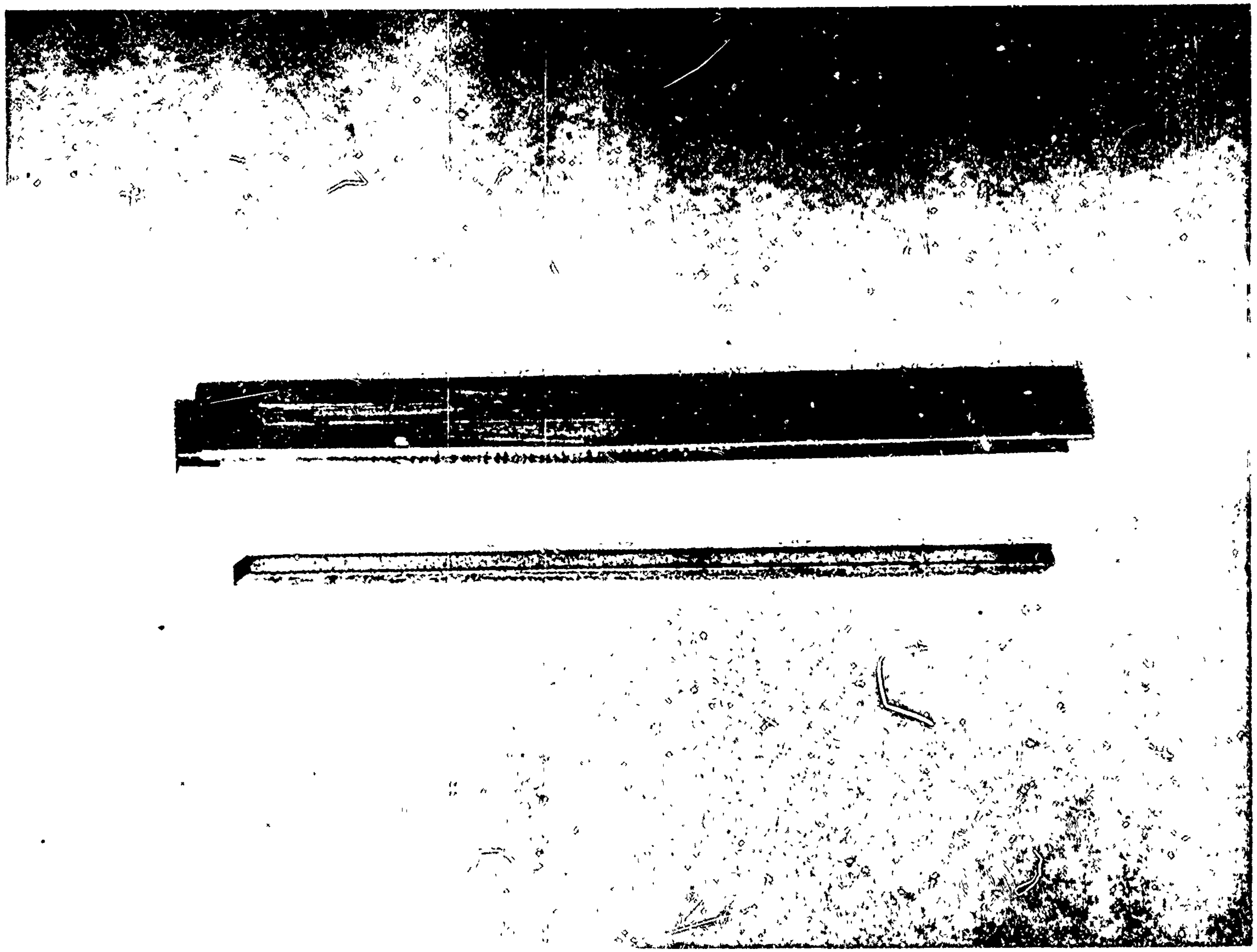

Fig. 9--Waveguide window assembly.

surfaces, insulator and feed-thru locations, and pump-out configuration, to accommodate the new waveguides and windows. Figure 10 shows the partially brazed gun-input waveguide housing and collector-output waveguide housing. The completed main collector body assembly including cooling jackets is shown in Fig. 11. This unit is vacuum tight and has been checked in the cooling system for coolant flow. Figure 12 shows the gun test unit which was used to check the gun before its installation into the final assembly.

7. X-BAND CONSIDERATIONS

Some preliminary calculations were performed on the possibilities of extending the basic design to X-band, with a 10-kw power level as the objective. However, until the basic design was proven at S band, it was not considered wise to initiate experimental work, since the circuit configuration might have to be modified. For this reason, the consideration of an X-band tube was limited to an examination of the finned structure which was used as the starting point for the S-band circuit, and some gun and beam calculations.

For the finned structure of Fig. 13, the propagation constant β_o as a function of frequency can be determined for an open periodic structure by the use of the following equation:

$$(\beta_o h) = (kh) \sqrt{1 + \left(\frac{\delta h}{Ld}\right) \frac{\tan(kh)}{(kh)}} \tag{2}$$

where

$$k = \omega\sqrt{\mu\varepsilon} = \frac{\omega}{c} = \frac{2\pi}{\lambda_o} \tag{3}$$

ω is the operating radian frequency and λ_o is the free-space operating wavelength. The other parameters are shown in Fig. 13.

The 0.020" thick fins used in the S-band tube are, because of practical reasons, as thin as can be used. Also d must be increased to at least 0.100" to accommodate the requirement for 10 kw of power. Because of these fixed dimensional requirements, it is not possible to directly scale the S-band model to X-band.

If the basic waveguide size is chosen to be 0.400 inch by 0.900 inch (WR-90 waveguide), the following dimensions can be chosen for the X-band tube structure:

$L = 0.040$ inch

$h = 0.300$ inch

$\delta = 0.020$ inch

$d = 0.100$ inch

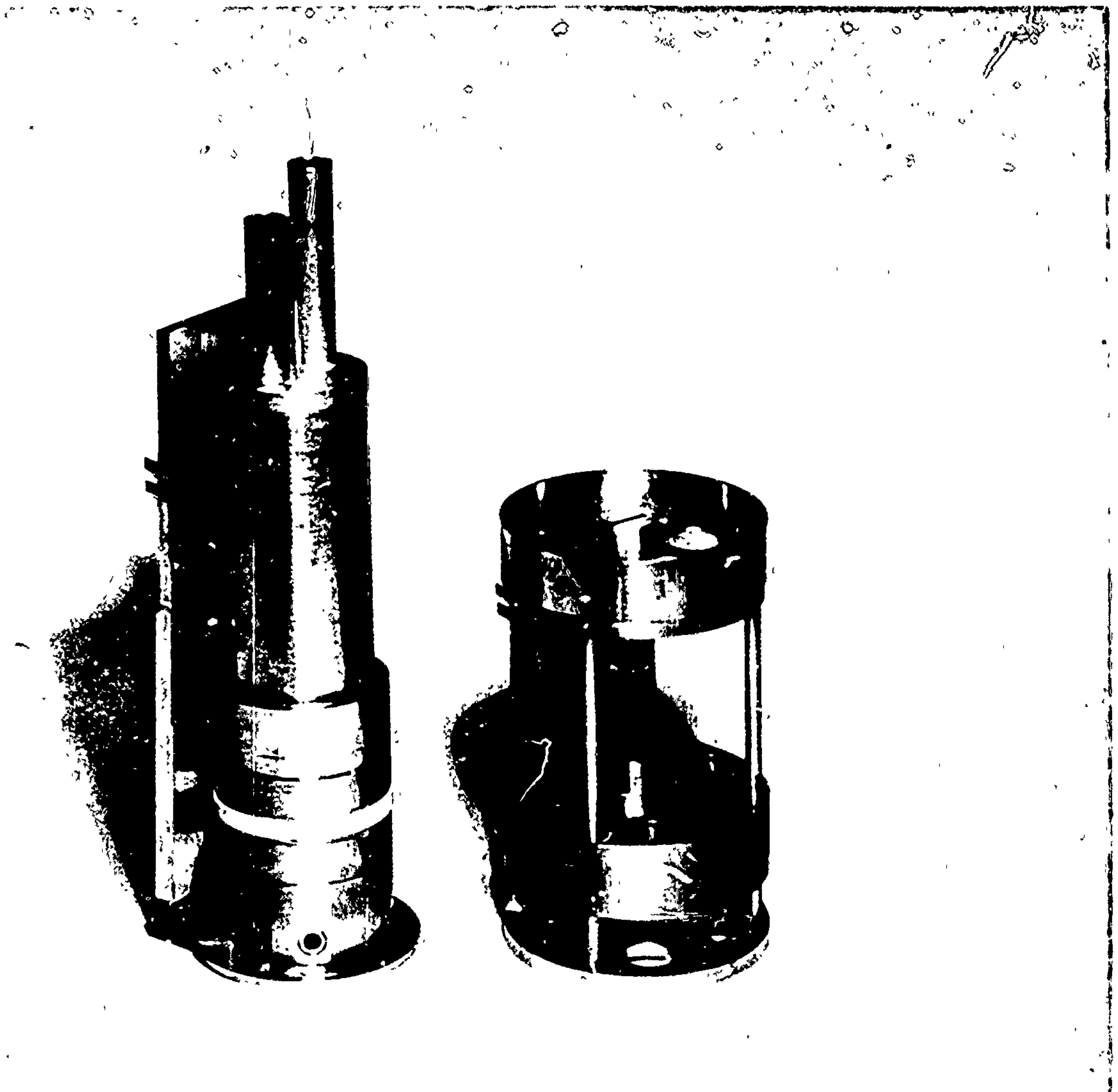

Fig. 10--Collector and gun assembly.

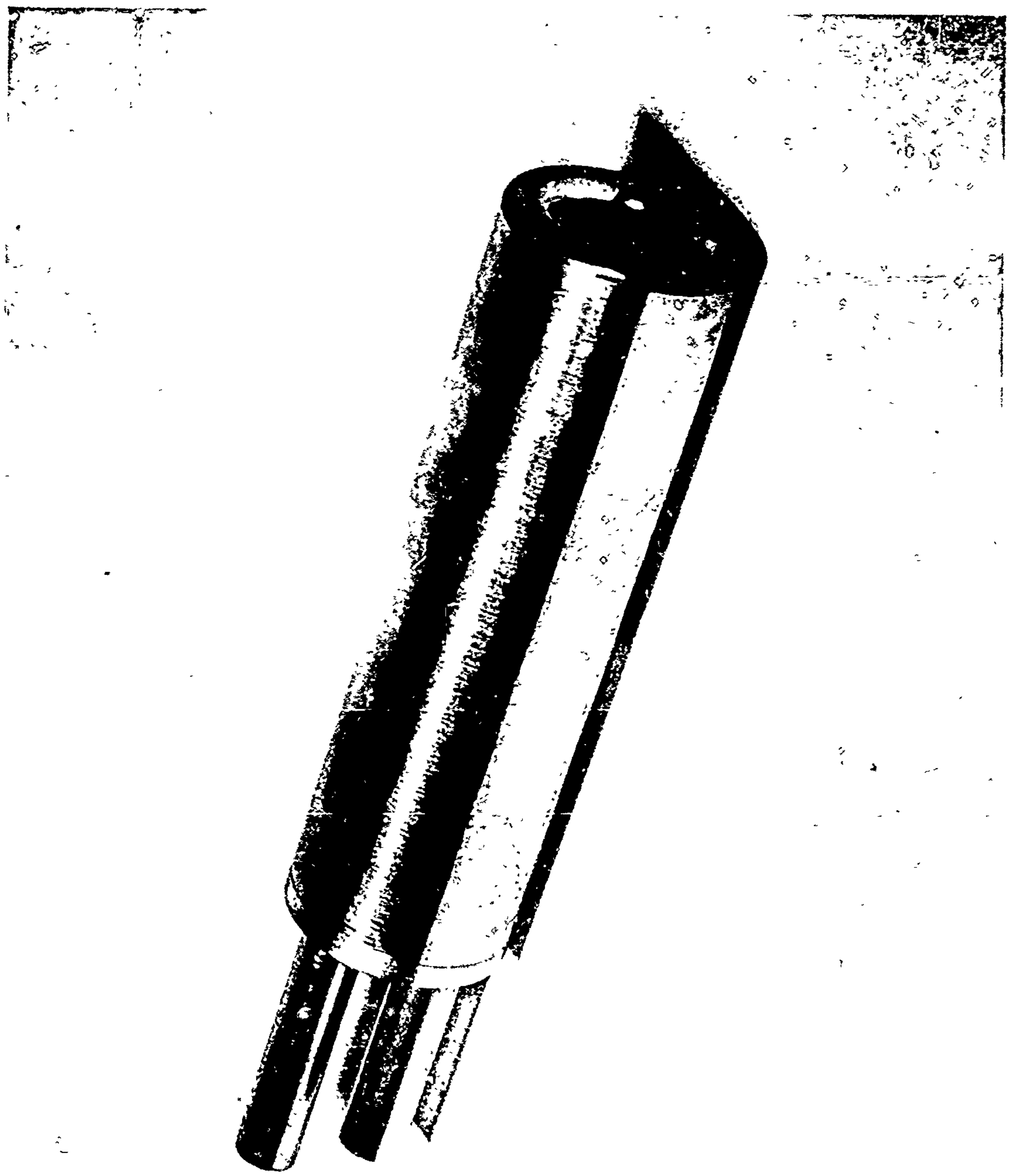

Fig. 11--Main collector body.

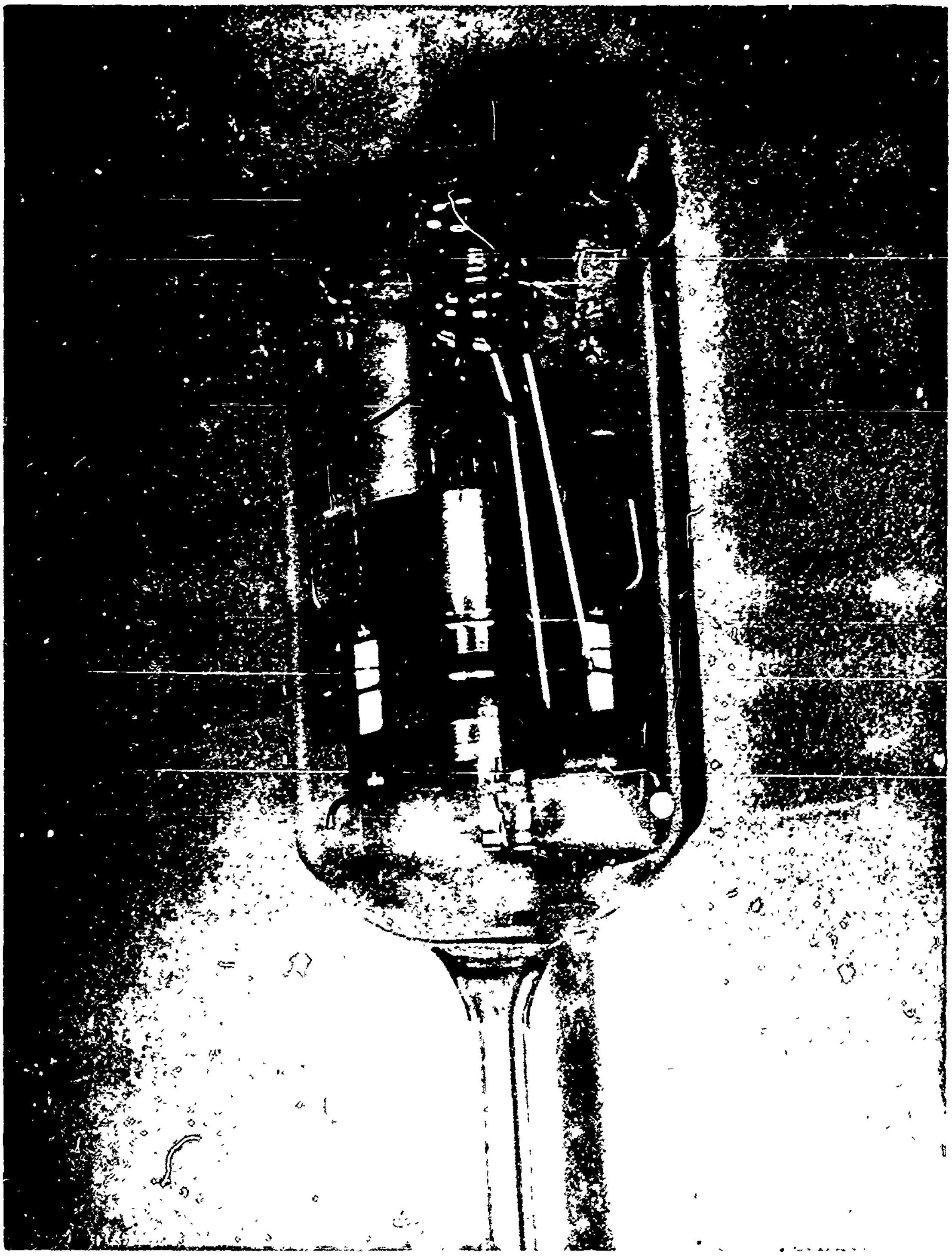

Fig. 12--Gun test assembly.

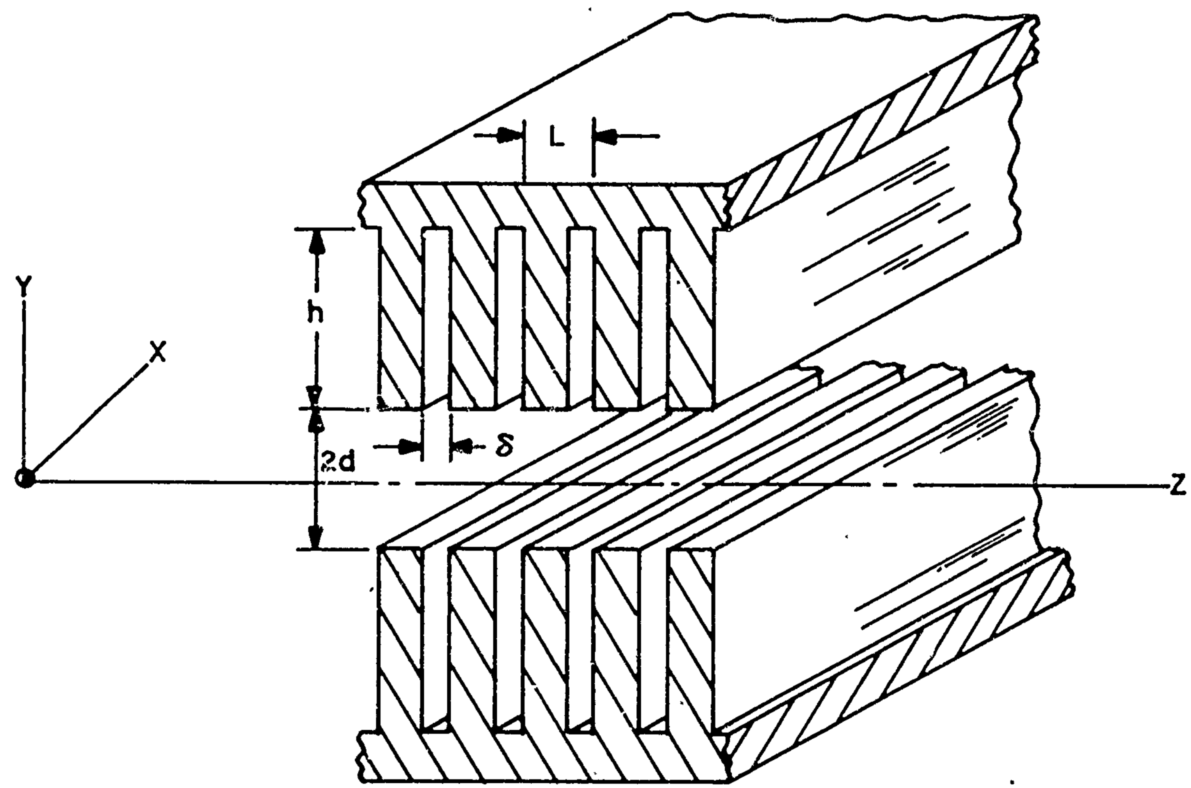

Fig. 13--Finned structure.

If an operating frequency of 8 gHz and a twist pitch of 1.44" are assumed, the calculated synchronous-wave phase velocity to light velocity ratio is 0.31. This requires an operating potential of 24 kv.

If an electronic efficiency of 30% is assumed, the required beam power will be 33-1/3 kw for 10 kw of output power. The beam current for V_0 = 24 kv would be 1.39 amps. The required perveance is then approximately 0.37 microperv, a reasonable number.

Our experimental evidence has indicated that the actual phase velocity (assuming a similar circuit configuration) will be somewhat higher so there will be some adjustment required in the above numbers, dimensions, etc. Also, the actual design will be dependent upon the test results of the S-band tube.

Preliminary X-band calculations indicate that the gun requirements are reasonable and that the X-band circuit can be of a practical size.

8. TUBE ASSEMBLY AND PROCESSING

All of the work performed during the third quarter was devoted to the final assembly of the prototype tube. Major difficulty was encountered with the waveguide windows and a further design modification was necessary before it was possible to complete the collector and gun assemblies and cycle them through the bake-out temperature range. The design change consisted primarily of making the kovar window frame an integral part of the waveguide and moving the window location away from the heliarc joint.

No difficulty was encountered in the stacking of the 1100-piece circuit section. Also the attenuator sections were easily situated. Further, the circuit stack was successfully sintered and placed in its stainless steel housing.

In general, heliarcing of the various sections of the tube proceeded as expected except in the region of the windows. This difficulty was alleviated in the design modification mentioned above.

It required a little over one week to process the tube. It was discovered at tip-off that a leak had developed in a kovar-to-stainless steel seal; also the input window developed a leak. These were patched by using glyptal and the tube was reprocessed.

The tip-off was unsuccessful because the tool malfunctioned. It was necessary to put a new tubulation on the tube and go through the process cycle again. Figures 14 and 15 show the tube on the vacuum station prior to tip-off. A new tip-off tool was obtained and this time the procedure was successful. The tube went to test at the end of the third quarter.

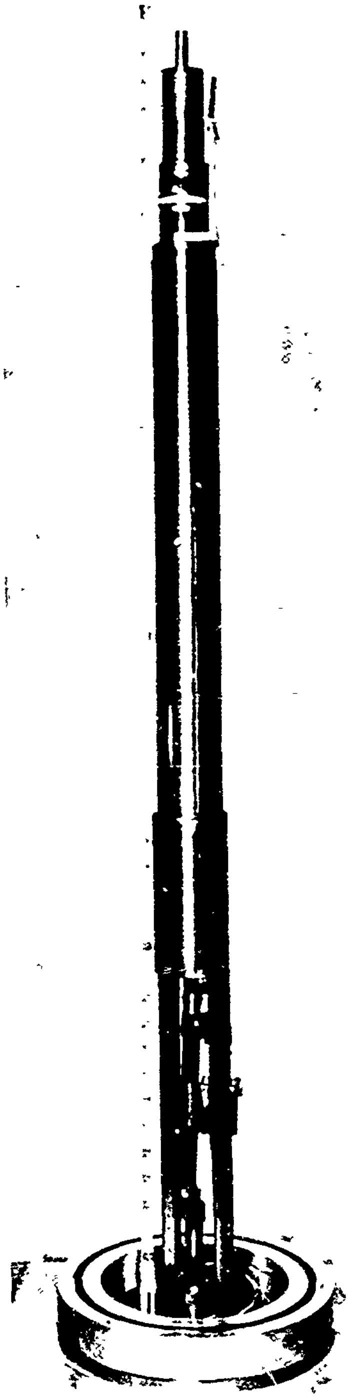

Fig. 14--Prototype transverse-wave tube mounted on vacuum station.

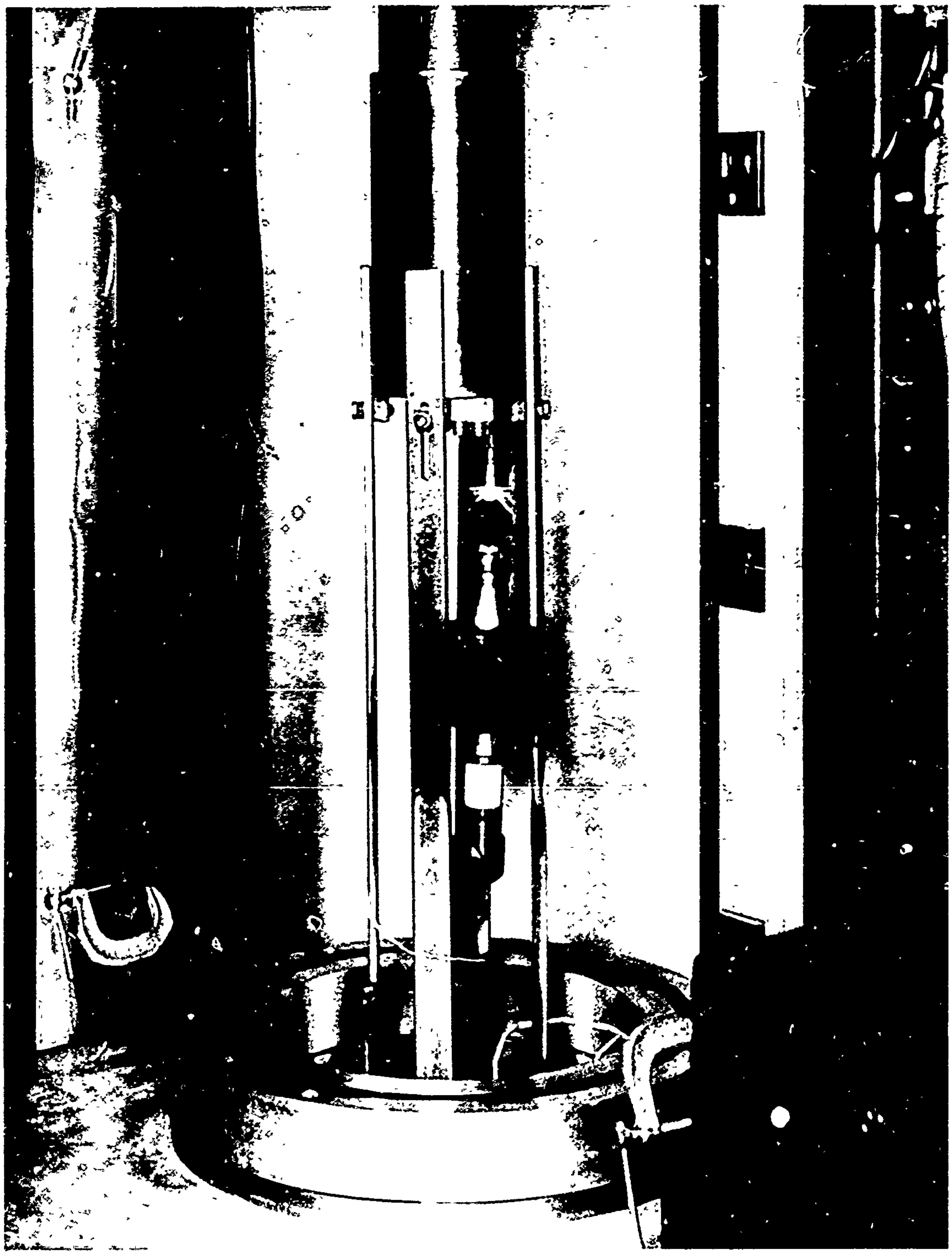

Fig. 15--Close-up view of vacuum station mounting.

9. TESTING OF THE EXPERIMENTAL TUBE

The testing began during the last week in October, with initial operation under cw conditions at low voltages. Initial outgassing made it necessary to raise the voltage slowly; however, normal transmission of the beam was observed at low voltages and reasonable focusing fields, such that tube alignment in the solenoid was accomplished with ease. RF drive was applied to the tube input at a level of about 0.25-0.5 watt, from a TWT amplifier. With the beam off, the output was measured, yielding a cold insertion loss of approximately 45 db at 4.5 gHz. With the beam on, a "signal" response was observed at the output for beam voltages above about 300 v, which represented 35-40 db "electronic" gain at about 2 kv. This signal response was quite sensitive to magnetic field, and both beam voltage and field had to be optimized to maximize the "gain". At about 3.5 kv, an oscillation set in whose frequency was found to be in the vicinity of 5.5 gHz, within a narrow range approximately 3 MHz wide. The oscillation presisted regardless of the polarity of the magnetic field, and it was relatively insensitive to field strength, in both frequency and amplitude. The output level of the oscillation was approximately 0.1 - 0.2 watts.

During these initial observations, measurements on the beam indicated that about 5-10% of the cathode current was intercepted in the gun region, and less than 10% on the rf circuit. However, since considerably higher beam voltages had to be employed, subsequent tests were performed with a pulser supplying the cathode voltage (the rf circuit was at ground potential), with all other electrodes operated from dc supplies. It was also noted that the beam-control electrodes were quite ineffective, and were therefore tied together, except for occasional checks at higher beam voltages.

The pulsed conditions applicable to the remaining tests were as follows: pulse width, approximately 5 μsec, pulse period 2.55 millisec (392 Hz PRF), pulse shape as shown in Fig. 16. The details of the pulse shape were essentially identical, whether measured as the cathode voltage (with a high-voltage probe), or as the collector current (through a series resistance). Thus while a flat-topped pulse was not attained, voltage and current measurements were quite repeatable, so long as they were always made at the same point on the pulse waveform (taken as the maximum point, for simplicity). The 10% undershoot observed on the cathode voltage pulse did not appear on the collector current pulse, showing that this was a characteristic of the pulser, not of the measurement equipment.

The peak voltage was gradually raised to the 10-kv level, allowing sufficient time for the appendage pump to handle the outgassing; this operation took several days. Measurements of

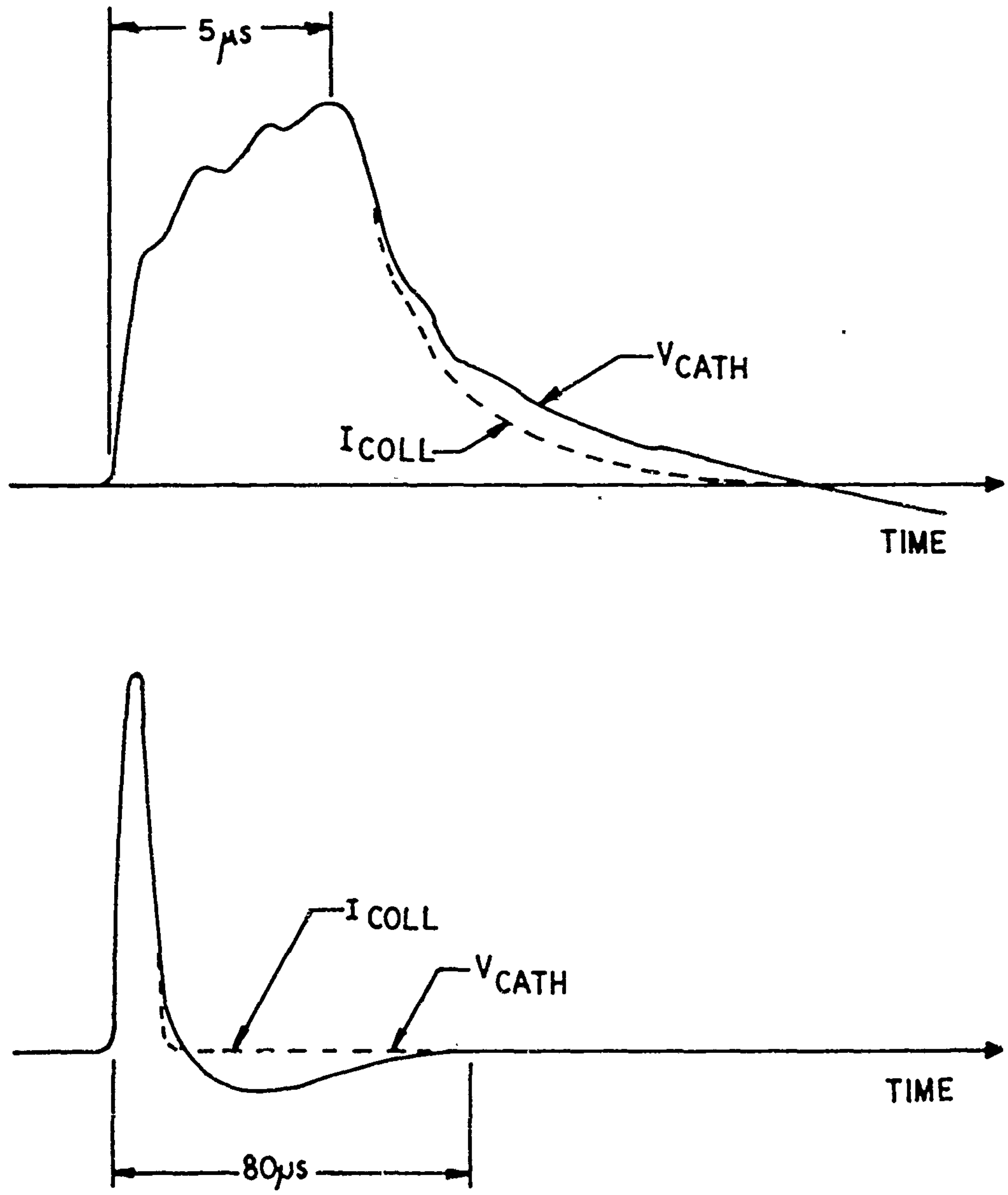

Fig. 16--Typical observed pulse shapes.

peak collector current vs. peak cathode voltage yielded the data shown in Fig. 17; also shown is the theoretical curve for perveance 0.5×10^{-6}, assuming no interception. In view of the 10-20% interception previously measured, the correspondence was considered to be satisfactory.

Measurements were made of the VSWR at each of the couplers. The output coupler appeared reasonably good over the band, below 2:1 from 4.1 to 5.3 gHz, and less than 1.5:1 over most of this range. The observed match was somewhat sensitive to output coupler position, as a result of the slip joint at the output window. The input coupler, on the other hand, exhibited a poor match everywhere except in the vicinity of 4.58 gHz, where the match was below 2:1 over a range only about 0.2 gHz wide. The match could not be affected by mechanical manipulation; the window joint is internal to the tube envelope at the input end.

At this point, since a better input match had been previously observed, we rechecked the cold insertion loss at 4.6 gHz, and found it to be about 63 db, as compared to the 45 db observed earlier. This measurement was repeated at several intervals during subsequent tests, and found to be about 60 db in each case. apparently some mechanical shifting in the input line internal to the tube had taken place, although the exact cause could never be positively identified. Subsequent rf measurements were thus restricted primarily to the 4.6 gHz region, where best input-coupler transmission could be obtained. A filter cavity was inserted between the tube output and the detector, to enhance the signal response and suppress the observed output due to the oscillation.

With the above setup, a search was made for a substantial signal response, over a wide range of voltages (up to 16 kv) and magnetic fields (0-2,000 gauss, both polarities) without finding any other than the low-level response mentioned previously. This response gave a maximum of about 45 db "electronic" gain at 4.6 gHz with an optimum beam voltage near 7.0 kv, and an optimum magnetic field of about 1,550 gauss, of either polarity. The B-field polarity affected the optimum slightly, but this was attributed to hysteresis and asymmetry in the solenoid-tube positioning; conditions could be restored, after a field reversal, by a minor readjustment of the tube position.

Primarily because of the insensitivity of this response to field direction, but also because of its low level, this signal response was believed to be a space-charge wave interaction, not a transverse-wave response. This signal response is virtually wiped out at voltages above about 9 kv, although evidence of its presence could usually be seen on the skirts of the pulse, as the voltage swept through the lower values. At the optimum beam voltage of 7.0 kv, the magnetic field was varied, with the result that the response went through a series of maxima and minima of decreasing

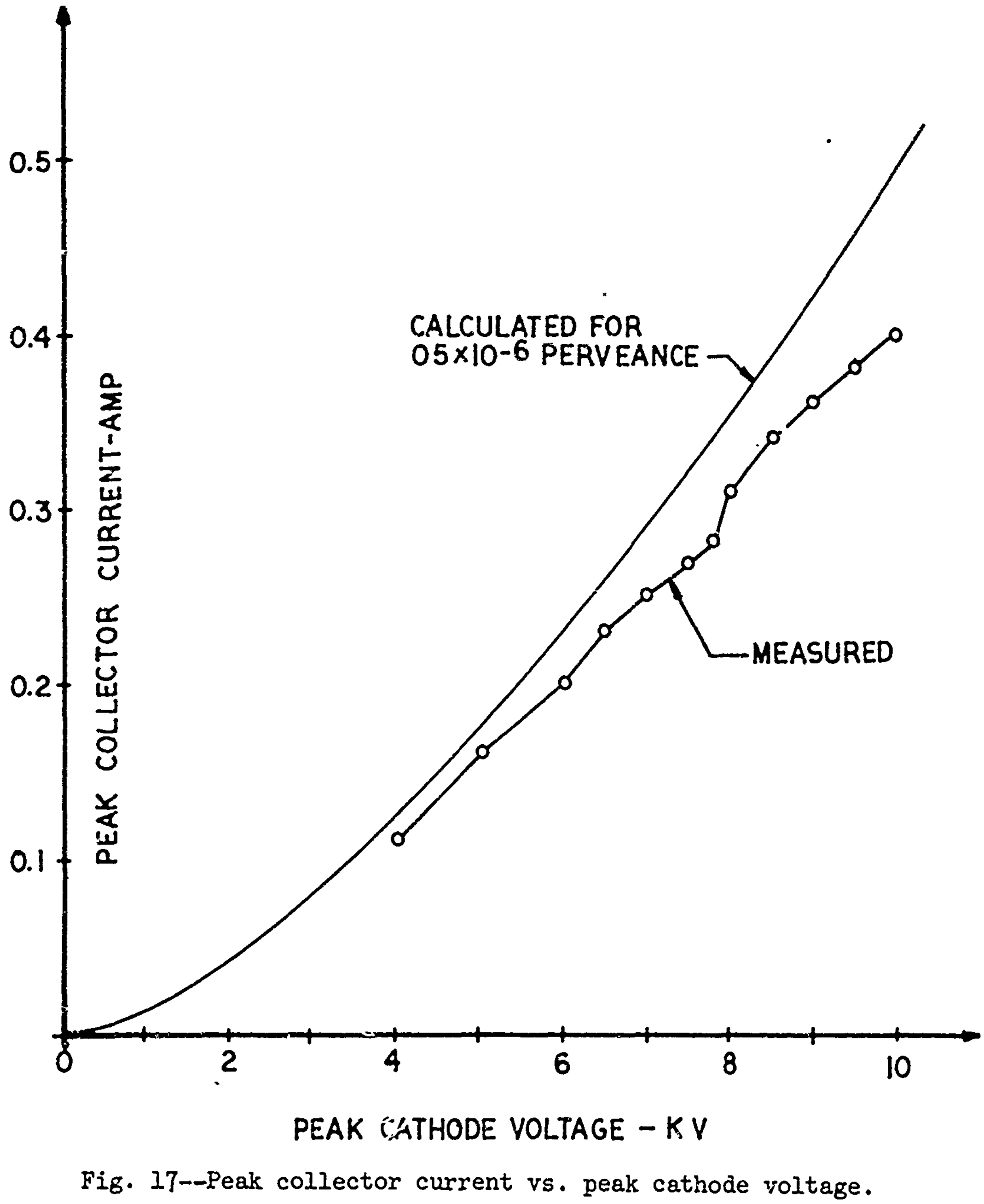

Fig. 17--Peak collector current vs. peak cathode voltage.

size, reminiscent of a (sin x)/x type response. This may have been partly due to focusing asymmetries, as the interception varied also with the magnetic field.

The spurious oscillations were studied, in an attempt to determine their nature, and assign an interaction mechanism to them. The first oscillation mode observed, as mentioned previously, occurred at voltages above about 3.5 kv, and a frequency of about 5.5 gHz; the frequency of this mode was independent of the magnetic field over a wide range (600-2,000 gauss) and quite insensitive to beam voltage (±10 MHz for changes of a few hundred volts). At higher voltages (above 7.2 kv) a distinctly different and stronger oscillation appeared, with the same frequency stability as the first mode, but at a slightly lower frequency (5.447 gHz vs. 5.495 gHz for the lower-voltage mode). Both modes appear unchanged when observed through a narrow-band wavemeter cavity, indicating spectral purity for each of the two distinct modes. These observations were made on <u>both</u> ports of the tube, indicating strongly that backward-wave interaction was involved. The power emerging from the input port was clean, while that from the output port contained other spurious components; however, the two modes identified above were present at both ports, at the same wavemeter settings.

With beam volt- in the 10-12 kv region, the output power in the 5.447 gHz mode was sufficient to cause crystal burnout on several occasions. In one measurement of the output from the <u>input</u> port, conditions were optimized to obtain the maximum available power (including stub tuners, etc.), with the result that approximately 2 watts peak was observed. While the effect of the internal mismatch could not be determined, it seems plausible that the internal available power could have been considerably greater, perhaps a few tens of watts.

A second effect associated with the stronger oscillation mode was observed at voltages above 9 kv: the collector current pulse begins to be distorted by interception, finally reaching complete beam collapse at 11-12 kv. This effect is polarity-sensitive, and was observed only when the north pole of the solenoid was adjacent to the gun end of the tube. The opposite magnet polarity yielded only minor effects on the beam current, nothing approaching beam collapse. With the beam voltage at 12 kv, and the magnetic field varied, the beam current shows two stages of collapse: a weak, sharp suck-out at about 1,130 gauss, which disappears for both higher and lower fields, and a strong effect which begins at 1,350 gauss and persists up to beyond 2,000 gauss, characterized by a steepsided and complete removal of beam current during a portion of the pulse. Simultaneous observation of the rf output shows that, during beam collapse, neither signal nor oscillation is present at the output coupler. Voltages up to 16 kv were applied; the beam current suck-out simply increased in width, corresponding to a greater fraction of the applied pulse which exceeded about 11 kv.

These observations were suggestive of a transverse-wave interaction in which the gain was sufficient to drive the beam into the rf circuit, and thus may well have been the only evidence of the desired synchronous-wave interaction. That this behavior was not obtained with reversed magnetic field suggested that the twisted circuit was involved, as it should be.

Efforts were made to find a signal (input) controlled effect associated with the beam collapse condition, without success. A search for the "missing" current during suck-out was made on each electrode, other than the collector; none was found, indicating that the current was intercepted on the rf circuit (grounded). By purposely misaligning the tube in the solenoid such that only a small part of the beam reached the collector end, and with signal applied at the input port, it was hoped that a signal-dependent effect could be observed; this also failed. A number of other minor experiments failed to shed further light on the situation.

Finally, at the end of the contract period, the tube was opened so that the circuit phase velocity could be re-measured, and an examination performed to uncover any possible explanation for the lack of expected results. The phase-velocity measurements confirmed the previous results almost exactly, with a 9.4 kv synchronous voltage at 4.2 gHz. No physical damage to the interior of the tube was observed, with the exception of a small pit burned in the stainless-steel decelerator disc just beyond the end of the rf circuit. It was not possible to determine how far the input coupler might have shifted; it appeared to be in approximately the correct position, ruling out a gross movement. No beam damage on any of the copper circuit discs could be observed, except for the normal darkening from cathode evaporation.

A final review of the theory likewise failed to reveal any reason for lack of synchronous-wave interaction.

10. CONCLUSIONS

Fabrication and testing of the first complete synchronous-wave TWT has been accomplished. Some design modifications were necessary on the vacuum windows and waveguide sections. The attenuator was developed and successfully fabricated, yielding a broadband well-matched loss characteristic. Assembly and processing was accomplished, with the only major problems being those due to window leaks and a vacuum failure at tip-off. After re-processing, the tube went to test with good vacuum, reasonable emission, and no high-voltage breakdown problems. Beam focusing was satisfactory, although little control could be obtained from the focusing electrodes, and about 10-20% of the beam was intercepted, primarily in the gun region. Thus, as far as the dc behavior was concerned, the tube was considered satisfactory for experimental purposes.

However, the rf performance was not as expected, in that a positive identification of synchronous-wave interaction could not be made. Two oscillations were found which had some of the characteristics of backward-wave modes, and one signal (amplification) mode was observed. All of these responses were dependent on the magnetic field and beam voltage, but were independent of field polarity, suggesting that space-charge waves rather than synchronous waves were involved. An apparent internal failure in the input line raised the insertion loss to about 60 db, preventing further detailed study of the signal response. At no time was a net insertion gain observed. The power levels were very small compared to the expected power capability of the tube.

A beam-collapse effect was observed, at relatively high voltages, which was dependent on the polarity of the magnetic field, and may have been a result of a high-gain transverse interaction with the twisted circuit. However, this contention could not be confirmed, since the effect could not be controlled by an input signal on the rf circuit.

There seems to be every reason to conclude that a gross flaw exists in the theory, perhaps in the analysis of the specific, rather complex, rf interaction circuit employed. Yet the approach taken was largely based on experimental measurements of the circuit parameters, with a minimum of dependence upon analytical predictions. There can be no serious doubt as to the reality of the synchronous waves, as previous work has established their principal characteristics, at least for lumped-coupler interactions at low-to-medium power levels. Were it not for the beam-collapse effect observed, we would probably be forced to conclude that the particular circuit employed was at fault; however, in this configuration the circuit was unfortunately rather well isolated from the input terminal by a poor match, and may not be entirely to blame for the negative results.

In our opinion, the most crucial point to be examined in any future work is that of the traveling-wave interaction process itself, preferably unhampered by the requirements for broadband circuit matches, good vacuum windows, and high-power tube techniques in general. There is sufficient merit in the twisted finned circuit that experiments should be pursued, perhaps in a demountable setup, to confirm its usefulness, or discover its flaw. Only after this has been accomplished should substantial efforts be expended on other aspects of tube design.

This contract is supervised by the Microwave Tubes Branch, Electron Tubes Division, ECL, USAECOM, Fort Monmouth, New Jersey 07703. For further technical information, please contact Mr. Arthur Gottfried, Project Engineer, Telephone Ext. 201/596-1229.

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13. ABSTRACT

Research and development work is described on a power amplifier tube employing transverse-wave interaction between the negative synchronous wave and a traveling circuit wave on a balanced structure. The theoretical advantage in this arrangement is the possibility of high-power amplification with high overall efficiency, due to the lack of longitudinal or transverse velocity modulation in the spent beam

The initial design parameters are reviewed, and modifications are discussed. The design and fabrication of the attenuator is outlined, and measured results presented. Modifications to the waveguide input and output sections, and to the vacuum windows, are described.

Consideration was given to a possible extension of the design to X-band at higher powers, although no firm extrapolation could be made at the present time.

Assembly and processing of the first complete tube is described, along with the difficulties encountered. Testing of the tube showed that the dc behavior was reasonably satisfactory, but the rf behavior was not as expected. The search for synchronous-wave interaction is outlined; while some indirect evidence of a transverse interaction was believed to have been observed, it was not possible to identify positively the desired amplification mode. The reasons for this failure are thought to be associated with the particular circuit employed, although no specific reason could be found.

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