A. THREE-CM MEDIUM-VOLTAGE TRAVELING-WAVE AMPLIFIERS

A number of tubes to operate in the region 1500 - 2000 volts have been built since the last report.

1. Glass-Wool Helix Supports

These supports were incorporated into an operating tube. The velocity of propagation along the helix was very nearly what it would have been in free space, as indicated by the beam velocity for optimum gain. The mechanical assembly of supports within the outer envelope was poor and the helix pitch was far from constant. Although the tube had about 50 - 60 db of lumped loss in the first quarter of the helix, it oscillated at about \( \lambda = 3.6 \text{ cm} \), with no evidence of longer wavelength oscillations. The operation was never clearly understood, as work on this tube was stopped in order to test the tubes described below.

2. Helix Supported by Glass Sheath

A number of tubes have been built with the helix mounted as indicated in Figure VIII-1.

![Figure VIII-1 Detail of 3-cm traveling-wave-tube helix construction.](image)

The last two tubes had the following characteristics:

\[ V_o = 1850 \text{ volts} \]

\[ i_{\text{Helix}} = 1 \text{ ma} \]

\[ i_{\text{collector}} = 1.5 \text{ ma} \]

Gain = 23 db

N.F. = 28 db
Helix: .058 inches I.D. x .006 wire dia x 46 turns/in. x 8 3/4 inches long. Lump loss of 40 db was provided by Aquadag painted on both inside and outside of the supporting glass tube as shown in Figure VIII-1. The gain was flat (±1 db) over 1200 Mc bandwidth. Figure VIII-2 shows gain and output power as functions of input power, and Figure VIII-3 shows incremental phase shift through the tube as a function of helix potential (beam velocity) for two different power levels.

Some tests on a noise reducing scheme attributed to Field were made. This scheme uses positive feedback around the tube. The idea being that the signal and feedback will add as voltage but the input beam noise and
feedback noise, being incoherent, will add as power. The preliminary tests showed that the noise figure could be made worse by negative feedback, but it remained nearly constant for any positive feedback up to the oscillation point. Even more curious, the output noise was a function of the phase shift in the feedback line. If the noise entering the helix is incoherent with that at the output, the phase shift should not affect the power addition. Further measurements will be made on this phenomenon.

3. Gun Design

Following the suggestion of Dr. C. C. Wang, a new electron gun for the 3-cm traveling-wave tube has been designed. The electrode profiles are simple rectilinear figures (Figure VIII-4) which are easy to fabricate accurately. In this way the curved electrodes used previously have been eliminated and the tolerance on the cathode positioning has been relieved somewhat. In determining the design, the dimensions varied in the electrolytic tank were: cathode potential electrode to cathode spacing $a$, and the large and small diameters of this electrode $d_1$ and $d_2$. The cathode to anode spacing and other dimensions are determined analytically according to the parameters of the required beam.

Preliminary tests of this gun indicate a considerable improvement over those used previously. Transmission efficiencies of over 90 per cent have been measured and the minimum beam diameter occurs at about the design distance from the anode aperture. This gun was designed to give a beam current of 5 ma at 2000 volts.

A special new tube is now being assembled so that a more accurate evaluation of this gun's performance can be obtained.

B. VELOCITY-MODULATED-INPUT TRAVELING-WAVE TUBE

Work on the construction of an experimental tube has continued throughout the last quarter. One tube reached the pumping stage, but attempts to

Fig. VIII-4 Pierce-gun using right cylindrical structures.
make it vacuum-tight were unsuccessful. At present, another tube is being readied for pumping, and a third set of metal parts has been assembled.

The cavity and gun are KR monel. The major difficulty has been the soldering of these parts to each other and to the OFHC waveguide, the Kovar cylinder and the molybdenum flange. It has been determined that the complete assembly can be soldered together with BT solder in an H₂ furnace if the KR monel parts are previously silver-plated. The molybdenum must, of course, be nickel-plated over the area where the solder is to flow.

Another operation which has been troublesome is the soldering of the window onto the end of the waveguide, but techniques assuring fair success have been found. Considerable assistance has been given us by the personnel of the Boston Electronics Plant, Sylvania Electric Products, Inc.

Following a suggestion of M. E. Hines of the Bell Telephone Laboratories, an approximate analysis of the tube has been made. The basis of the work is Pierce's analysis of the traveling-wave tube (1). The initial conditions imposed by the velocity modulation are matched to the three waves in Pierce's solution. The analysis is subject to Pierce's assumptions of small-signal, so that the velocity of the electron entering the helix is a sinusoidal function of time. In the work that follows, Pierce's notation (with some additions) will be used, for ease in reference.

If \( V_i e^{j\omega t} \) is the voltage across the input-cavity gap, the electrons at the start of the helix will have an a-c velocity given by:

\[
v = \frac{V_i}{2V_o} u_o e^{j\omega t - j\omega d/u_o},
\]

where the helix begins at a distance \( d \) from the gap.

The a-c current at the start of the helix must next be calculated. We can write, under the usual small-signal approximation,

\[
q = \frac{1}{2} \frac{\partial^2 \phi}{\partial t^2} + e^{j\omega t} u_0 e^{j\omega t - j\omega z/u_o}
\]

differentiating, we obtain,

\[
\frac{\partial q}{\partial t} = u_0 \frac{\partial \phi}{\partial t} + e^{j\omega t} \frac{\partial u_0}{\partial t} e^{j\omega t - j\omega z/u_o}
\]

Using the equation of continuity of charge, assuming \( q \) is of the form \( q = q(z)e^{j\omega t} \), and

\[
v(z,t) = \frac{V_i}{2V_o} u_o e^{j\omega t - j\omega z/u_o},
\]

where \( z = 0 \) at the gap we obtain:
(VIII. TRAVELING-WAVE TUBES)

\[ \frac{dq}{dz} + j\frac{w}{u_0} q = j\frac{w}{u_0} \frac{V_1}{2V_0} u_0 e^{-j\frac{wz}{u_0}}. \]

The solution of the differential equation is

\[ q(z) = j\frac{w}{u_0} \rho_0 \frac{u_0 V_1}{2V_0} e^{-j\frac{wz}{u_0}} + q(o)e^{j\frac{wz}{u_0}}. \]

To find \( q(o) \), consider that charge density cannot be changed instantaneously, and, at the gap, \( p(o) = 0 \). Hence \( q(o) = \rho_0 v(o) \) or \( \rho_0 (V_1/2V_0) u_0 \). Substituting this, \( \rho_0 u_0 = -I_0 \), and \( z = d \), we obtain for the a-c current at the start of the helix,

\[ q = -I_0 \frac{V_1}{2V_0} (1 + j\frac{w d}{u_0}) e^{j\frac{w z}{u_0}}. \]

We can now calculate the amplitudes of the three forward waves excited on the helix. From Pierce's paper, we write

\[ v = -\frac{n}{u_0} \left( \frac{E_1}{\delta_1} + \frac{E_2}{\delta_2} + \frac{E_3}{\delta_3} \right), \]

and

\[ q = \frac{j n w}{u_0} I_0 \left( \frac{E_1}{\delta_1} + \frac{E_2}{\delta_2} + \frac{E_3}{\delta_3} \right). \]

To solve for \( E_1 \), one more equation is needed. If no power is initially started down the helix,

\[ 0 = E_1 + E_2 + E_3. \]

All of the last three equations assume tacitly that the field distribution of these three waves is the same at the start of the helix so that voltages rather than powers may be added. This is not strictly true. Solving for \( E_1 \),

\[ E_1 = \frac{V_1 e^{-j\frac{u_0 d}{d^2}} \frac{\delta_1^2}{\delta_1^2} \left[ (\delta_2^2 - \delta_3^2) - \frac{u_0 d}{d^2} (\delta_1^2 \delta_2^2 - \delta_2^2) \right]}{\delta_1^2 (\delta_3 - \delta_2) + \delta_2^2 (\delta_1 - \delta_3) + \delta_3^2 (\delta_2 - \delta_1)}. \]

In the case of a lossless helix, with the electrons traveling at the velocity of an unperturbed wave, the \( \delta \)'s can be found analytically, and they are

\[ \delta_1 = (0.866 - j \times 0.5) \beta c, \]
\[ \delta_2 = (-0.866 - j \times 0.5) \beta c, \]
(VIII. TRAVELING-WAVE TUBES)

\[ \delta_3 = j\beta C, \]

Then

\[ E_1 = \frac{\beta CV_1}{2} e^{-j\omega t_0} e^{-j\pi/2} \left[ e^{-j5\pi/6} - \beta C d + j\frac{C}{2} \right]. \]

The power gain of the tube in decibels is

\[ G = 10 \log \frac{P_{\text{out}}}{P_{\text{in}}}. \]

If the impedance of the cavity including beam loading is \( Z_1 \),

\[ P_{\text{in}} = \frac{V_1^2}{2Z_1}. \]

Let the quantity in brackets in the expression for \( E_1 \) above have an absolute magnitude \( A \). At the output end of the helix, the magnitude of \( E_1 \) is given by

\[ |E_1| = \frac{\beta C A V_1}{2} e^{0.866\beta C L}, \]

If the tube is long enough so that the other waves are negligible compared to \( E_1 \), the output power will be

\[ P_{\text{out}} = \frac{|E_1|^2}{2} = \frac{\psi}{2} \left( \frac{BC A V_1}{2} \right)^2 e^{1.732\beta C L}. \]

Then, if we put \( \beta L = 2\pi N \)

\[ G = 20 \log \left( \sqrt{\frac{\psi}{Z_1}} \beta C A \right) + 47.3CN - 9.54. \]

This is identical with Pierce's expression (his equation 36) with the addition of the first term. If the product \( \left( \sqrt{\frac{\psi}{Z_1}} \beta C A \right) \) is greater than unity, there will be a gain advantage over a conventional traveling-wave tube of equal helix length.

It is interesting to make a somewhat optimistic estimate of the possibilities. Some reasonable values for the quantities are:

\[ \psi = 2 \times 10^{-5} \text{ ohms}^{-1} \text{ cm}^2 \]
\[ Z_1 = 3 \times 10^5 \text{ ohms} \]
\[ \beta = 23.2 \text{ cm}^{-1} \]
\[ C = 0.04 \text{ (dimensionless)} \]
\[ A = 1 \text{ (dimensionless)} \]
The product is then 2.27 and the gain advantage is roughly 7 db. If it is assumed that the only source of noise within the tube is the shot noise in the beam, and that the cavity has no effect on this noise, a noise figure can be calculated with relative ease. The calculation is also subject to Pierce's assumption regarding noise. The result is

\[ F' = 1 + \frac{8\varepsilon_0 V_o^2}{Z_1 k T I_o A^2} \approx \frac{8\varepsilon_0 V_o^2}{Z_1 k T I_o A^2} \]

For a conventional traveling wave tube

\[ F = \frac{4\delta^2 e V_o C}{kT} \]

The ratio of the two is

\[ \frac{F'}{F} = 20 \frac{V_o}{I_o} \frac{1}{Z_1} \frac{1}{A^2} \]

Substituting the values used before (\( V_o = 1800 \) volts, \( I_o = 0.005 \) amperes), the ratio is

\[ 0.091 \]

which seems to be a remarkable reduction of noise figure.

At present, an investigation of the effect of the cavity on the shot noise in the beam is underway so as to check the validity of the assumption made above.

C. **LOW-VOLTAGE THREE-CM TRAVELING-WAVE AMPLIFIER**

1. **Helix Assembly**

Much effort has gone into a suitable mechanical support for the helix. The quartz capillary tube described last time was not sufficiently straight nor were the inner and outer walls concentric. We have now gone to a construction illustrated in Figure VIII-5, in which the quartz support consists of two rectangular slabs with axial grooves, that are clamped around the helix. The slabs can be ground very accurately and the helix can be laid in place with a minimum disturbance of the pitch.

2. **Gun Design**

Two different gun designs have been tested, neither of which were successful. The designs were of the usual Pierce type; but since the perveance was very low (350 volts, 50 \( \mu \) amps) the anode-cathode spacing was large.
As a result, the thermal velocities of the electrons (in volts) were comparable to the potential set-up near the cathode, and there was a lot of sideways spreading. A new tank design has just been run off using a .060 inch dia cathode which allows a reduction in the anode-cathode distance, thus giving the thermal velocities less time in which to act.

3. **Tubes**

A number of tubes have been built while waiting for a good gun design. These tubes have used "haywire" gun assemblies giving only a few microamperes of collector current. None of them has shown more than 0 to 1 or 2 db of net gain, and no noise figures have been measured.

D. **DENSE ELECTRON BEAMS IN AXIAL MAGNETIC FIELDS**

As the problem of solid cylindrical beams in axial magnetic fields has been treated by Dr. C. C. Wang (in an unpublished report, Sperry Gyroscope Co.) attention has been given to producing and focusing hollow electron beams. The analysis involves the determination of a potential function associated with the radial motion. The problem then consists of determining radial space-charge and electrostatic potential distributions consistent with the initial assumptions. At present there are no definite results to report.

**Reference**