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LOW NOISE TRAVELING-WAVE TUBES

Verification of Fundamental Theory and Explanation of Higher Order Effects

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Low Noise Traveling-Wave Tubes. Verification of Fundamental Theory and Explanation of Higher Order Effects

The theory of low-noise traveling-wave tubes has been developed by Peter and Bloom, Pierce and Danielson, and others. Fluctuations of electron current and velocity, originating at the cathode, are transformed by the electron gun and drift regions of the tube in much the same way as acoustical waves are transformed by horns. The transformed fluctuations excite the input of the slow-wave circuit, and contribute to the noise figure. The first order theory specifies the type of transformation required in the gun for minimum noise figure. It also predicts a minimum noise figure.

The experimental work described in this bulletin is in part a justification of the one-dimensional theory. Beyond the limits of validity of this theory, interesting and important effects are measured, associated with the condition of the cathode, focusing conditions in the gun, and residual gas. Theoretical explanations have been found for these phenomena, leading to suggestions for ultimate improvement in the minimum noise figure.

The effect of higher order space charge waves in the beam is analyzed for the first time, giving a plausible explanation for peculiar "growing-wave" effects which hither-to had gone unexplained. This theory also predicts a *lower* noise figure than the one-dimensional theory, thus placing the performance of the best low noise tubes in better agreement with theory.

The design of optimum-performance electron guns for low noise traveling-wave tubes is also considered, since many of the experimental results suggest improvements in this part of the tube.

Introduction To Theory of Low Noise Traveling Wave Amplifiers

The theory of low noise operation of traveling wave amplifiers has been developed by Watkins[1], Bloom and Peter[2], Pierce and Danielson[3], and Haus and Robinson[4]. Although the methods of approach differ considerably, the results of the theories are essentially the same. Given a cathode emitter of a specified temperature, assuming that the noise velocity fluctuations at the cathode are those given by Rack[5], and that full shot noise current exists at the potential minimum, the theories predict a certain minimum noise figure. For oxide cathode temperatures, this predicted minimum is about 6 decibels. Since measurements resulting in 5 db or lower noise figure have been made[6] it seemed worthwhile to evaluate the present theory, and to determine experimentally the limits of its validity.

The Bloom and Peter theory is representative. Noise introduced in the electron beam at the cathode (or the potential minimum) is transformed by the accelerating and drift regions following in the electron gun. In a drift region, for example, the noise current and noise velocity should, according to the first order theory, follow a regular standing-wave pattern. In an accelerating region, the noise current and velocity are not periodic functions of distance, but it has been shown[4] that the space charge waves have important conservation properties.

The most physically pleasing model of the space charge wave transformation in the electron gun and drift regions, is the transmission line analogue of Bloom and Peter[7]. The conservation rules for the space charge waves on an electron beam are the same as for power on a transmission line, and a "characteristic impedance" may be defined, for the electron beam. The accelerating regions of an electron gun may be represented by tapered-impedance sections of a transmission line, since the "characteristic impedance" of the beam is a function only of the beam voltage, current, dimensions and operating frequency.

The relative sensitivity of an rf slow wave circuit to fluctuations of velocity and of current in the incoming beam depends on the degree of coupling to the beam (C), on the beam's space charge (QC), and on the circuit loss (d). Using Pierce's traveling wave tube theory, Bloom and Peter[2] introduced the current and velocity fluctuations of the beam into the expression for the amplitude of the growing wave. By adjusting the noise current standing wave ratio (η) of the beam, and the position of the noise standing wave relative to the circuit input (ψ), a minimum excitation of the growing wave by the beam noise is obtained. This determines the minimum noise figure. Bloom and Peter[2] found that if the space charge wave transformation is optimized, the minimum noise figure of a traveling wave tube depends only on the two parameters QC and d, plus the amount of noise introduced into the beam at its origin.

For the first order theory described above, one needs to know three quantities to specify the noise of the beam. These are: the velocity fluctuations, the current fluctuations, and the correlation between the two. The optimization procedure, fortunately, is not modified by the presence of correlation, nor is the space charge wave transformation or noise standing wave pattern; the noise figure may, however, be either increased or reduced by the presence of correlation. At the cathode itself, the current fluctuation is known to be given by the shot noise formula, and the velocity fluctuation by the Rack[5] formula. The noise-smoothing properties of the potential minimum of a space charge limited diode are well known at low frequencies; just how this current smoothing mechanism operates at microwave frequencies is still not completely understood. Since experimental evidence does not reveal a marked dependence of noise figure on cathode current density, the question of noise reduction by smoothing is still very much an open one.

Description of the Noise Measuring Apparatus

The purpose of the experimental work described here was: (1) to determine the applicability of the noise minimization procedure quantitatively; (2) to measure the noise current and noise figure and from them attempt to determine the actual noise fluctuations at the potential minimum, and to what extent they are correlated; (3) to determine the factors, if any, which cause digression from the simple theory; (4) to measure the noise wave transformation properties of electron guns.

To accomplish all this requires both noise current and noise figure measurements *on the same beam*, as a function of the position along the axis of the beam. The rf assembly used for these measurements is shown in Fig. 1; it consists of a resonant cavity (operating at 3000 mc) and a traveling wave circuit (helix) assembly, complete with input and output couplers. It slides within a precisely machined brass tube, which is covered by a glass envelope (Fig. 2). The coaxial lines from the rf assembly pass through vacuum seals in the end of the tube. The electron gun and the collector are fixed also within the precision tube. A set of thin molybdenum tapes forms a square drift region around the beam and prevents depression of potential and ion trapping; as the rf assembly is pulled along the axis, the tapes pass over rollers and around the cavity and helix assemblies.

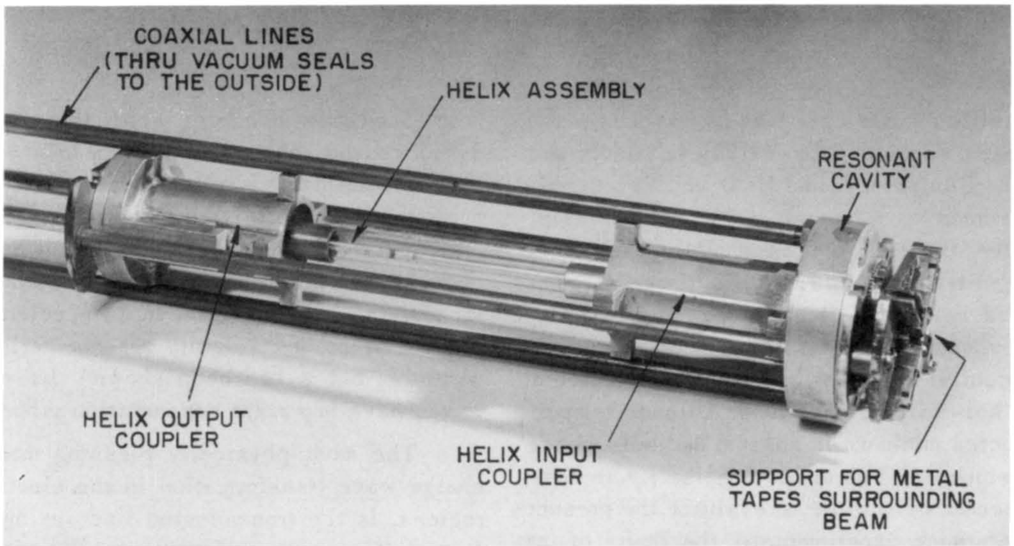


Fig. 1 – Movable cavity-helix assembly.

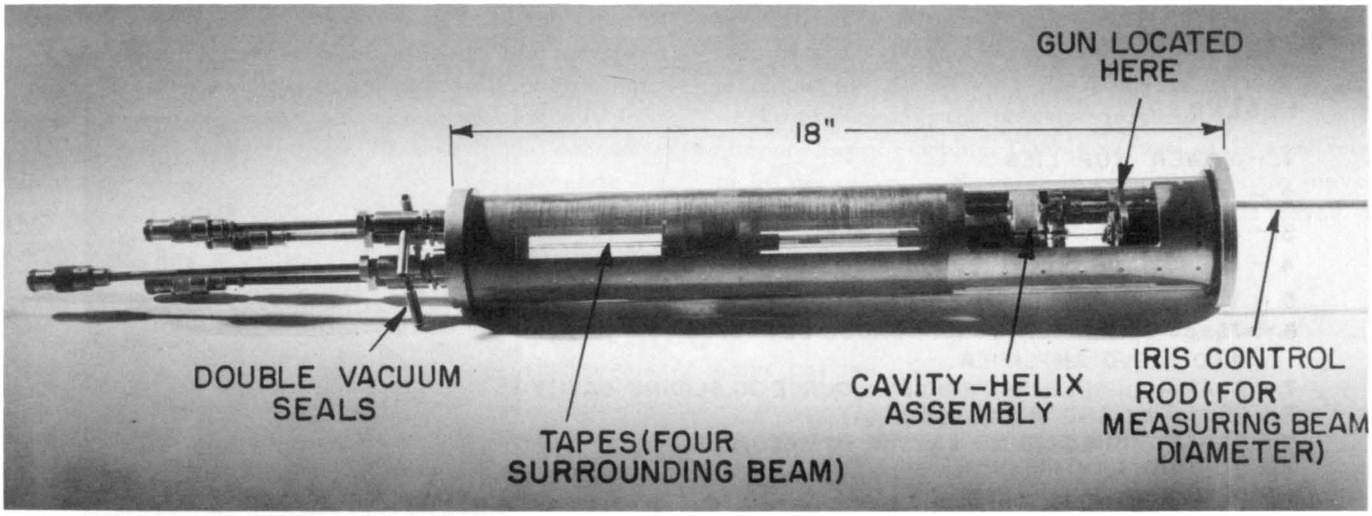


Fig. 2 – Demountable noise measuring tube (removed from vacuum system).

Conventional receivers are too insensitive for measurement of noise current in a low current electron beam; consequently, this measurement must be made using a synchronous detection method similar to the Dicke radiometer[8] (See Fig. 3). The electron beam is square-wave modulated at 75 cps and the noise picked up by the resonant cavity is first detected, then amplified in a tuned 75 cps narrow band amplifier, then finally detected by a phase discriminating detector. The limit of sensitivity depends only upon the speed of response desired. Since the circuit would otherwise be dependent on the constancy of amplifier gain, comparison is made between the beam noise and the noise output of a gas discharge tube noise source fed to the cavity through a second coupling loop. By modulating the discharge tube 180 degrees out of phase with the electron beam's modulation, the noise signal from the gas discharge source may be made to cancel the 75 cps signal from the electron beam. By adjusting the attentuator in the noise source circuit, the total detected output is reduced to zero. In the actual circuit, this zeroing procedure is carried out by a servomechanism. The attenuator reading is available as a continuous measure of the electron beam noise current. The noise current is automatically plotted vs the cavity position by an X-Y recorder. The circuit is shown in Fig. 4.

The same elements are used for the measurement of noise figure. The attenuator in the noise source circuit is adjusted to make the noise output of the helix twice as much with the noise source on as with the noise source off; the beam is no longer modulated. In our circuit, a switched detector produces a zero output voltage (at 75 cps) when this 2:1 power ratio is attained. The detector signal is then used to control the servomechanism, and thus, the attenuator, just as before.

The accuracy of the measurements depends upon

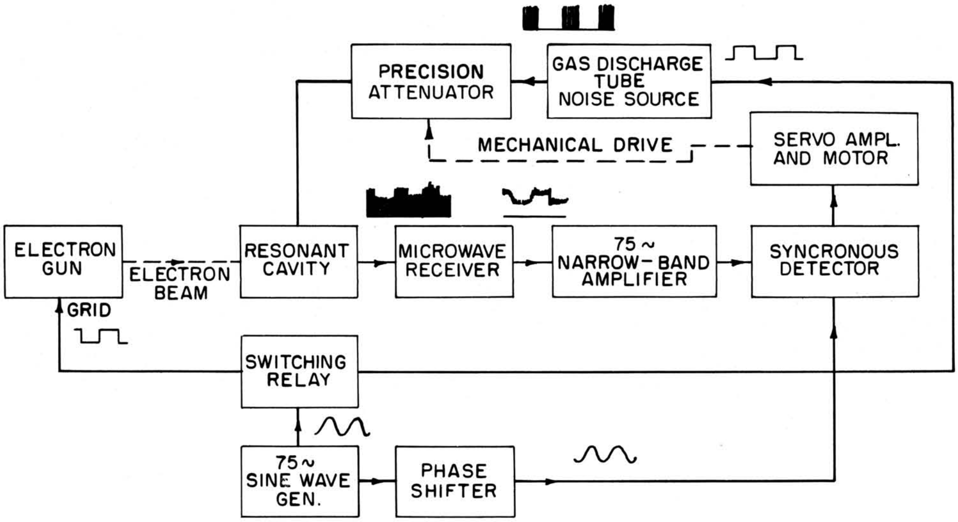
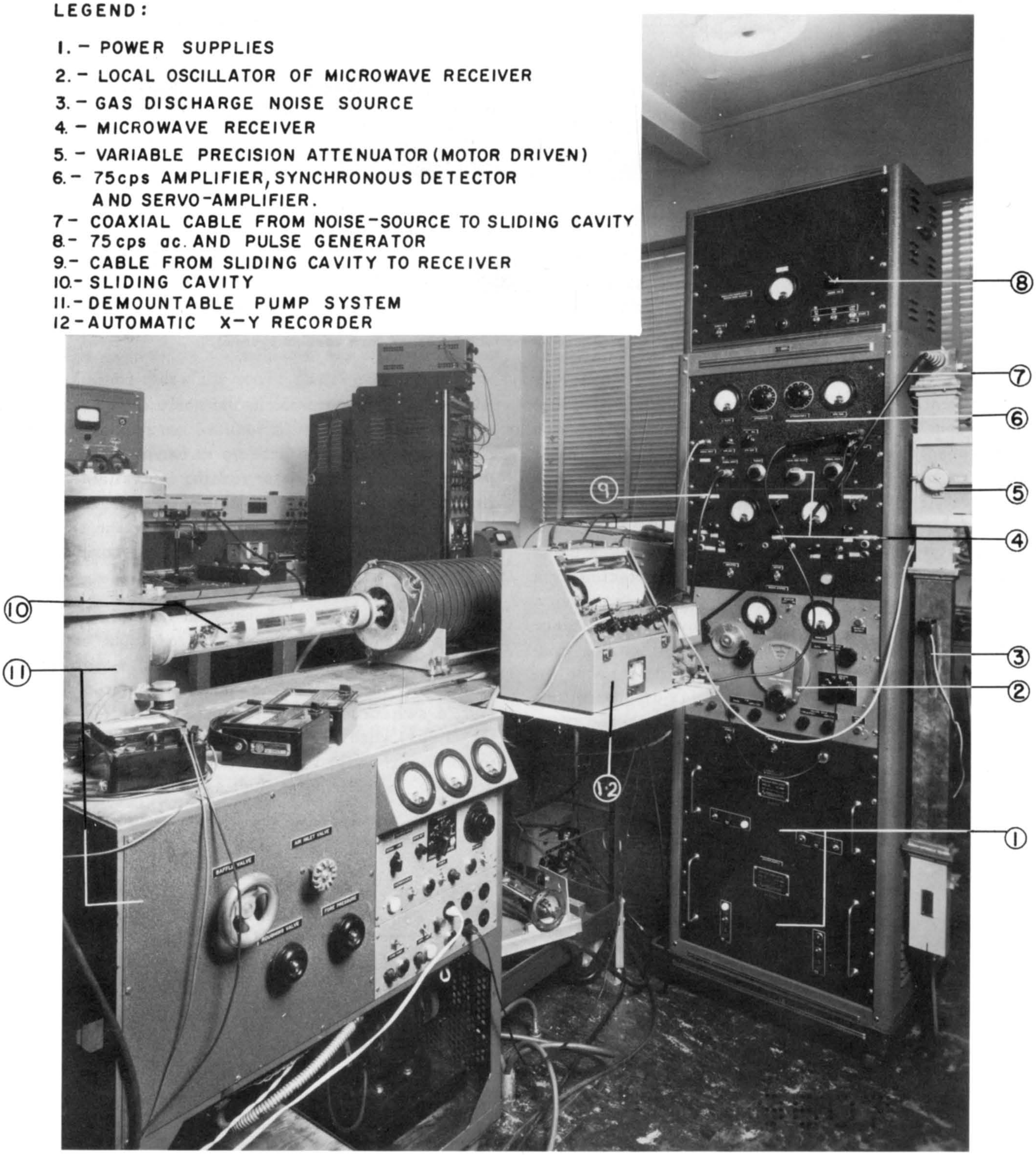


Fig. 4 – Block diagram, noise current measuring apparatus.



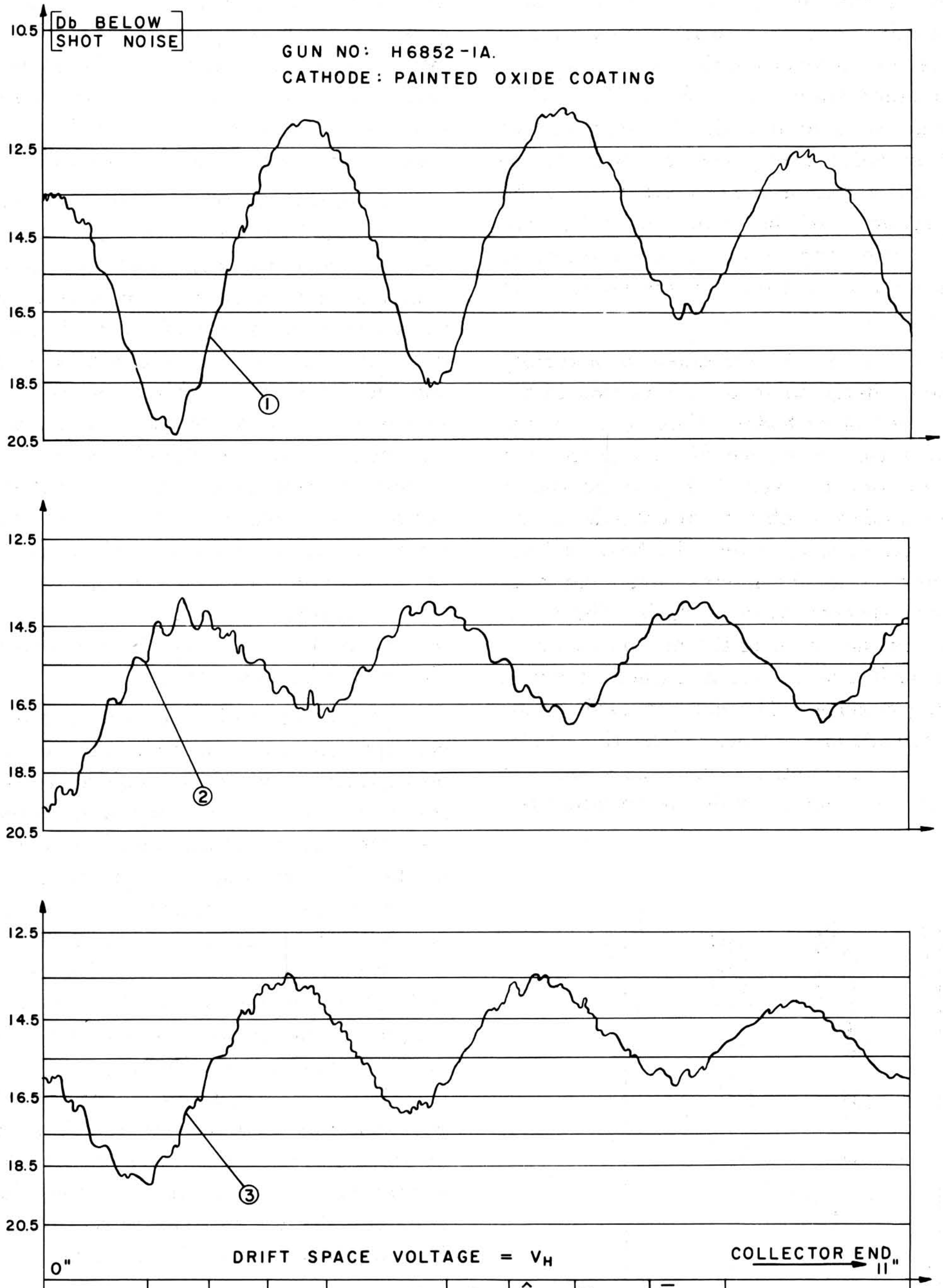
LEGEND:

1. – POWER SUPPLIES
2. – LOCAL OSCILLATOR OF MICROWAVE RECEIVER
3. – GAS DISCHARGE NOISE SOURCE
4. – MICROWAVE RECEIVER
5. – VARIABLE PRECISION ATTENUATOR (MOTOR DRIVEN)
6. – 75cps AMPLIFIER, SYNCHRONOUS DETECTOR AND SERVO-AMPLIFIER.
7 – COAXIAL CABLE FROM NOISE-SOURCE TO SLIDING CAVITY
8. – 75 cps ac. AND PULSE GENERATOR
9. – CABLE FROM SLIDING CAVITY TO RECEIVER
10. – SLIDING CAVITY
11. – DEMOUNTABLE PUMP SYSTEM
12 – AUTOMATIC X–Y RECORDER

Fig. 3 – Automatic noise measuring system.

the accuracy of the gas discharge tube noise source. Repeatability over periods of one month is of the order of 0.2 db. Sensitivity is of the order of 0.1 db, and the speed of response gives a reading in approximately one second. A complete run, made by pulling the rf assembly from one limit of its motion to the other (about 12 cm) consumes less than three minutes. It is difficult to appreciate the speed and accuracy of this system unless one has tried to make such measurements manually.

The vacuum system to which the demountable tube is attached is all-metal, and contains a large number of O-rings and valves. A large liquid air trap enables us to reach as low as 10^{-8} mm Hg in pressure, after several weeks of pumping; the pressure is about 3×10^{-8} mm Hg after one day of pumping. Double vacuum seals were found to be necessary at the sliding coaxial lines, to prevent poisoning the cathode when the rf assembly is moved.



CURVE NO.	V_{G1}	V_{a1}	V_{a2}	$V_{a3} = V_H$	B	$\hat{I}_{COLL}$	I_{HEATER}	$\bar{I}_{COLL}$	
1	-16.3V	70 V	130V	400 V	470 G	265μA	2.7 A	135μA	
2	- 0.4	40 V	"	"	"	"	"	"	
3	-8.2	55 V	"	"	"	"	"	"	

Fig. 5 – Noisiness as a function of gun potentials.

Verification of the One-Dimensional Noise Figure Theory

The noise measuring system just described was fitted with an electron gun of the type to be described later. Initial measurements were made, with only the resonant cavity in the tube. The general appearance of these noise currents vs distance curves will be seen in Fig. 5. The noise current does *not* follow a periodic pattern, as the first order theory assumes. The noise current minimum nearest the electron gun is lower than any other; likewise, the first maximum is also smaller. Since those effects which produce this non-periodicity are essentially additive to the first order effect, we have used the first maximum and minimum to calculate the "noisiness" of the beam. If the first order theory applied exactly, the product of maximum and minimum noise current times the "characteristic impedance" of the beam should be constant, and invariant with respect to the transformation within the gun. It should depend only on the noise input at the potential minimum.

Curves like those of Fig. 5 were taken for a variety of conditions of space charge wave transformation in the gun, and for several types of cathodes. These early measments were made at a time when we did not appreciate some of the unknown factors involved. In Fig. 6 are shown noisiness values measured for each type of cathode; these are the lowest value for each cathode. The best cathode measured was a surface-polished tungsten matrix cathode; the worst was a dense-sprayed oxide cathode. The reference level used here is the value of the noisiness which would be expected from full shot noise and Rack velocity, zero correlation being assumed. The data on oxide cathodes is probably tremendously influenced by the conditions of operation in the demountable tube; the same type of cathode, in a sealed-off tube, has delivered noise figures below that predicted by the first order theory.

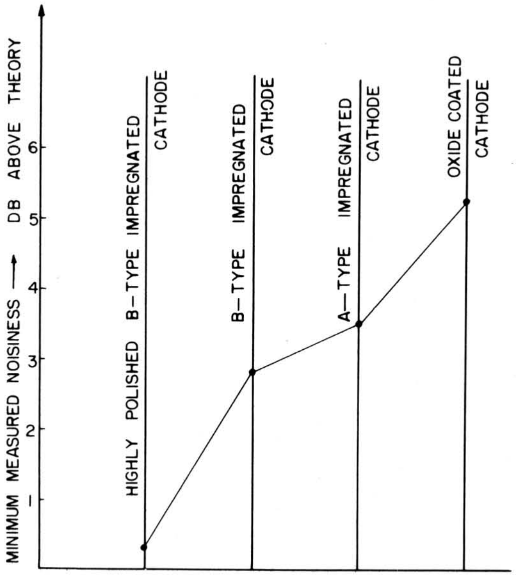


Fig. 6 – Noisiness vs cathode type.

Subsequent to these measurements, the cavity-helix assembly was mounted in the tube, and both noise current and noise figure measurements were made with the same gun adjustments. Because operation of the cavity and the helix at *exactly* the same frequency would have caused undesired coupling, the two were operated at frequencies about 100 mc apart, which was sufficient to prevent coupling, but not enough to alter the noise characteristics of the beam. The Bloom and Peter theory specifies, for a given QC and d, optimum values for the standing wave ratio η and the position of the input ψ; these optimum values lead to an optimum noise figure. From this theory it is also possible to compute the noise figure when the space charge waves are *not* optimally transformed.

A number of runs of noise current and noise figure were made. From the noise current data, the position of a noise current minimum, and the noise current standing standing wave ratio were obtained. From the known and measured performance of the helix as a signal amplifier, the values of QC and d could be computed. With these and the *measured noisiness* of the beam, the theoretical values of the minimum and maximum noise figures (vs. distance) were calculated, as well as the theoretical circuit position ψ at which minimum noise figure should occur. Then from the noise figure measurements, experimental values of minimum and maximum noise figures and of ψ for minimum noise figure were found. The rather close agreement between theoretical and experimental values is shown in Fig. 7. The values of ψ are in particularly good agreement.

This, we feel, established the correctness of the concepts on which the first order noise figure theory, and optimization, are based. The near-perfect agreement between theoretical and measured values of noise figure was obtained by making an allowance of 0.15 db for loss in the rf input coupler; this brought the minimum noise figure curves into coincidence. The relation between the minimum noise figure and the noisiness is a function of the correlation between the fluctuations of current and and velocity at the potential minimum. From the data, the calculated correlation was zero, within the limits of errors of the measurement, leading us to the conclusion that correlation is negligible. From the data taken, it was not possible to determine to what extent noise current smoothing takes place at 3000 mc. A number of experimental observations, at RCA and elsewhere remain unexplained by the first order theory, in spite of the verification just described. These are:

(1) Measured noise figures, in sealed-off tubes with oxide cathodes, with values up to one decibel less than predicted by the first order theory.

(2) Measured values of beam noisiness several

decibels in excess of those predicted by the first order theory.

(3) Non-periodic patterns of noise current standing waves.

In the following sections, we shall attempt to explain these deviations from the first order theory.

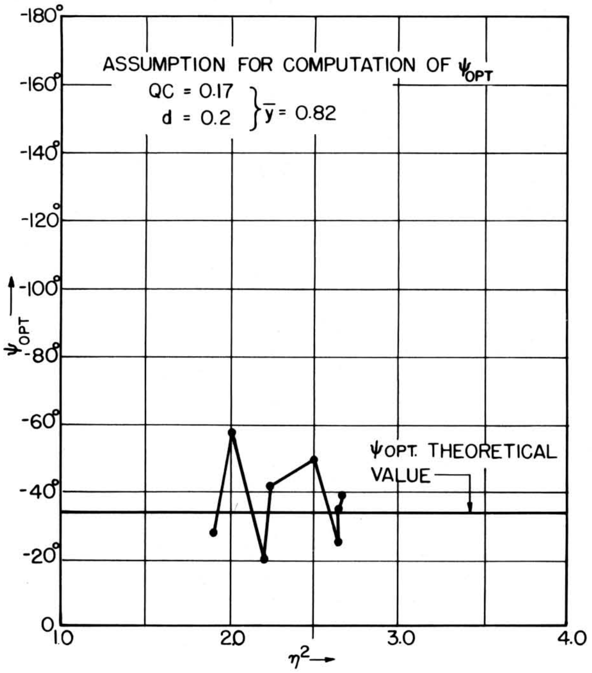


Fig. 7a – Measurement of ψ_{OPT}.

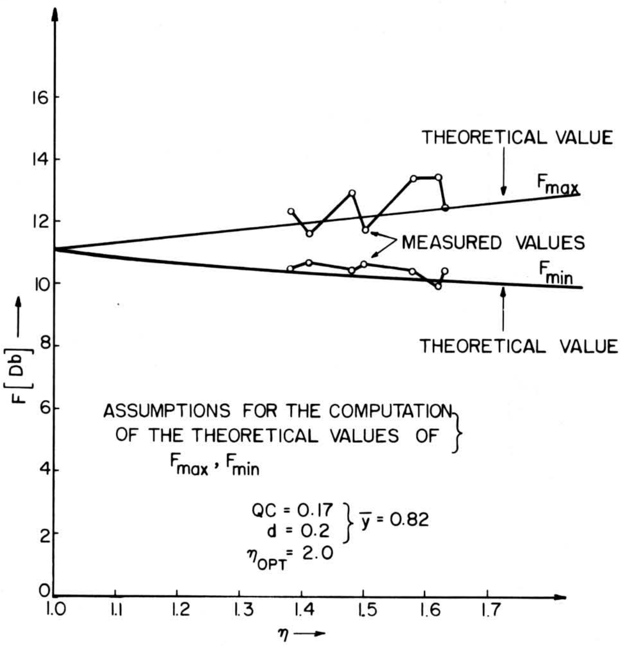


Fig. 7b – Measurement of F_{min} and F_{max}.

Geometrical Effects and Higher Order Space Charge Waves

The one-dimensional first order theory mentioned earlier considered the properties of the space charge waves on the beam to be expressible in terms of a velocity fluctuation v and a current fluctuation i, representing the rms values at a single frequency. Since the actual space charge waves in any electron beam have velocity and current density fluctuations which are dependent on the position in the beam cross-section, at best v and i can represent the amplitudes of a single mode of space charge waves. As Hahn[9] and others have shown, the space charge waves which propagate in an electron beam are infinite in number; in structure, they are similar to the modes of a circular waveguide (except that in the beam, all modes can propagate, and there is no cutoff frequency). For our purposes we may forget all but the axially symmetrical modes, since these are the only ones which can couple to an axially symmetrical circuit.

The assumption of a uniform shot noise density and Rack velocity fluctuation over the cathode surface, uncorrelated from point to point, leads to the excitation of not only the fundamental, but also all of the higher order modes. Each of these modes is transformed differently by the electron gun and drift region, just as two different modes in a circular waveguide would be transformed differently by a tapered waveguide impedance transformer. The growing wave of the helix is excited by each of the modes, but the degree of coupling of the higher order space charge waves to the helix is very small. If we make the assumptions that each of the modes of the beam is individually optimized, and that all modes are independent, we can calculate the excitation of each mode at the cathode, multiply it by the coupling factor to the helix, and finally compare the various modes' contributions to noise figure with the first order theory, as shown in Fig. 8. To achieve the mode independence and fulfill the assumptions, it was necessary to assume that the beam completely fills the drift space throughout the electron gun and drift regions. The results are surprising. The contribution to noise figure of the fundamental mode is never more than 69 percent of the total. The second order mode, if optimized, contributes 14 percent of the total, and the higher order modes than the second, successively less. Of greatest importance is the fact that the contributions of *every mode* are less at large $\gamma_o b$ (the beam circumference measured in units of electronic wavelength). Even though it is not possible to optimize every mode, this reduction of noise figure at high $\gamma_o b$ should still be realizable. Data on tubes built at several locations indicate that low voltage operation and a large beam diameter results in a low noise figure.

The values of η and of ψ for minimum noise figure have been found to be dependent on the particular space charge wave mode in question. The higher modes require a higher standing wave ratio of noise current and the helix must for these modes be located nearer to a noise current minimum. These requirements are fortunately not at variance with the operation of electron gun space charge wave transformers; it appears practical to optimize the first two modes, and possibly the third, by use of a rather complex electron gun. The minimum noise figure would then approach the value given by Fig. 8; this can be several decibels below the value given in the first order theory.

Higher Order Effects That Tend To Increase Noise Figure

Cathode Non-Uniformities

There are several ways in which an actual cathode may differ from the ideal homogeneous structure assumed in the first order theory. These include: non-uniform activity and emission density, emission from pores or cracks in the surface, and non-uniform coating resistivity. These non-uniformities may give rise to either a variable depth of potential minimum over the surface of the cathode, or non-uniform emission velocity. Since the potential minimum operates, in a space charge limited beam, to make the current density nearly uniform, it is the variation of emission *velocity* which is of the greatest interest to us. Fig. 9 shows two of the ways in which a non-uniform electron velocity may come about. If the focusing magnetic field were infinite, there would be no mixing of electrons from different points on the cathode surface, but since it is not, the initial transverse velocities of the electrons carry their paths across one another, as shown in Fig. 9.

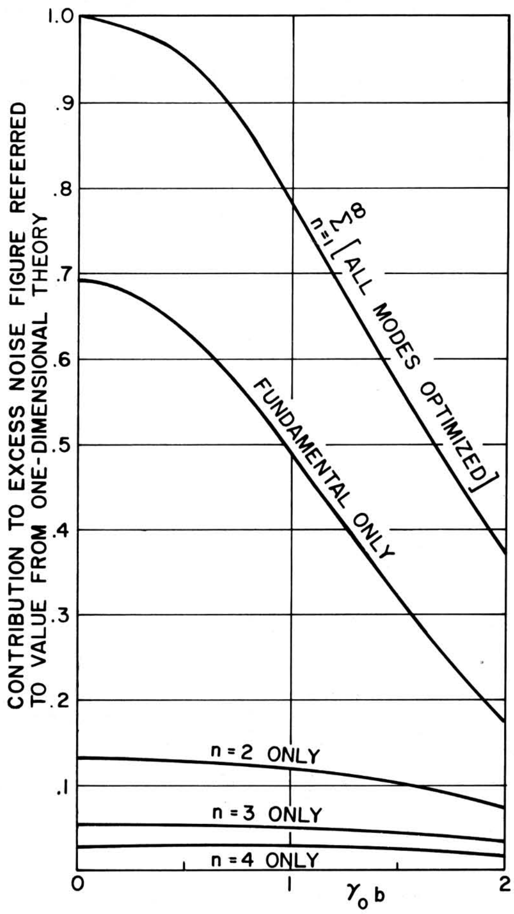
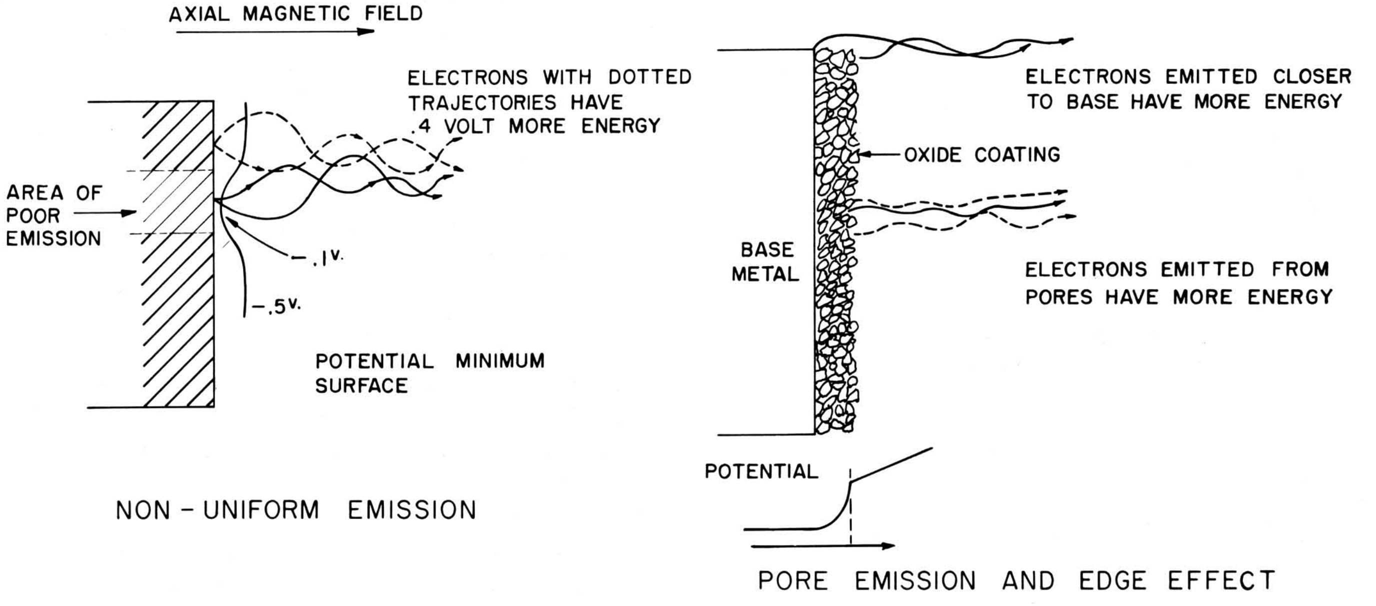


Fig. 8 – Contribution to excess noise figure referred to value from one-dimensional theory.

The mixing of electrons of different emission velocities produces a composite beam having a greater spread of axial velocities than the temperature of the cathode



NON - UNIFORM EMISSION

PORE EMISSION AND EDGE EFFECT

Fig. 9 – Effect of cathode non-uniformities.

would ordinarily produce. The effect on noise figure is just the same as that of an increase in cathode temperature, i.e., it increases. In Fig. 10 is shown the calculated increase in beam noisiness due to the perfect mixing of two electron groups of equal current and temperature, as a function of their separation in emission velocity. C_m is the factor by which the beam noisiness must be increased. Cathode measurements and theory have shown that the drop in voltage within an oxide cathode coating is of the order of one volt. Most of this voltage drop occurs near the surface, because of the non-linear resistivity of the semiconducting coating This large drop makes the effect of emission from pores or crevices in a cathode surface a likely source of excess noise in oxide cathodes having rough surfaces and high coating resistance. The mixing effect may be one cause for the lack of success in attempts to build low noise tubes with magnetically shielded cathodes; in the absence of a magnetic field, the transverse excursion of the electrons may carry them from one edge of the beam to the other, providing almost complete mixing of all velocity groups, within a short distance from the cathode.

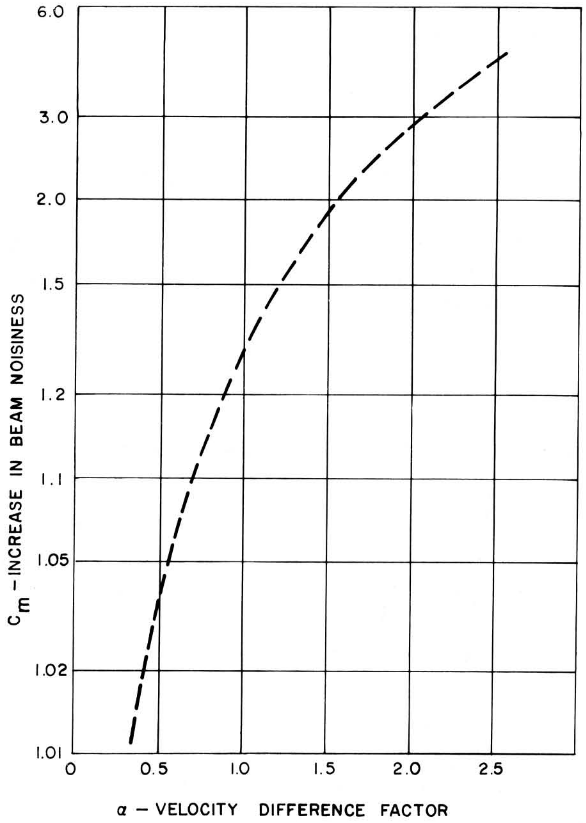


Fig. 10 – Increase in beam noise due to mixing two streams of equal current. Lower velocity limits zero and $\alpha\sqrt{kTc/m}$ resp.; compared with stream having zero lower velocity limit.

Matrix cathodes do not suffer from the coating resistance problem, however, measurements of the emission density from such cathodes have indicated a large difference in activity from point to point. This may cause variable potential minimum depth from point to point, which in turn gives the undesired difference in velocity of electrons emitted. Low current density operation will allow the potential minimum to locate at some distance from the cathode and reduce this effect. A low current density is also desirable in the oxide cathode, since the potential drop within the coating is a function of the emission current.

Effect of Residual Gas Pressure

Measurements were made to attempt to determine the precise effect of residual gas pressure in a low noise amplifier. Fig 11 illustrates the typical increase of noise figure in the demountable system as a function of increasing gas pressure. The constitution of the gas in unknown, but a fair assumption is that it is largely nitrogen, which is not trapped by the liquid nitrogen trap.

A theory was developed, based upon the simple assumption of partition noise distributed along the beam; when an electron collides with a gas molecule, it is assumed to be removed from the beam (actually, those electrons which are changed in velocity very little by collision may increase the velocity fluctuations in the beam; because of the complexity of this problem, it has not been completely solved). The shot noise introduced into the beam is transformed in the gun and drift region and finally influences the rf circuit.

Functional agreement between this theory and our measurements was observed. This means that the noisiness and the noise figure increased with distance along the beam and varied with pressure in the manner predicted by the theory. Quantitatively, however, the measured increase of noisiness exceeded the theoretical

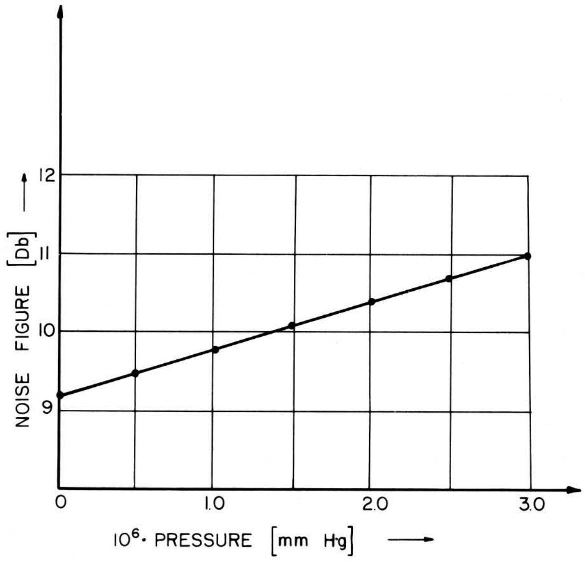


Fig. 11 – Effect of gas pressure on noise figure.

value by a factor of four; the noise figure increased by an amount twelve times greater than the predicted value. In addition to the neglect of introduced velocity fluctuations, the unknown constitution of the gas and the lack of an accurate value of collision probability could have influenced the agreement between theory and experiment.

Electron Lens Effects

In some of the earliest measurements the beam noisiness appeared to change somewhat as a function of the voltages applied to the electron gun. Noisiness was found to increase whenever the interelectrode voltages became very large, or when the difference in the fields between adjacent electrodes became large. We suspected the dc focusing conditions of being the source of this increase, and consequently built a special electron gun. In addition to the normal set of electrodes, this gun carried two additional ones at the end away from the cathode. When the three final electrodes were operated at the same potential, operation was conventional. When the next-to-last electrode was lowered from its normal 650 volts to zero potential, however, the noisiness was observed to increase by several db. (See Fig. 12).

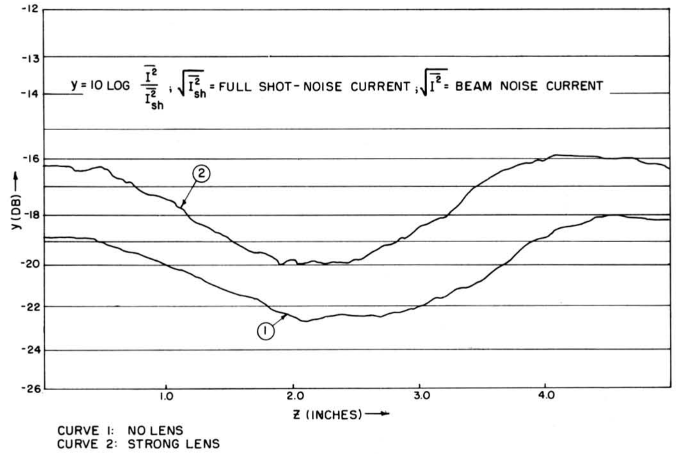


Fig. 12 – Effect of an electron lens on beam-noise.

We have developed what seems to be an adequate explanation of this effect. In an electron beam, the axial electron velocity fluctuations are reduced as the beam is accelerated from cathode potential to rf circuit potential. The transverse electron velocity fluctuations remaining unchanged by these essentially axial electric fields, it follows that at beam potentials of more than a few volts, the transverse velocity fluctuations considerably exceed the axial fluctuations. As a result of its transverse fields, an electron lens tends to equalize the transverse and axial fluctuations. Therefore, part of the larger transverse velocity fluctuations in the beam can be transformed by an electron lens into additional axial velocity fluctuations. Since the circuit of a conventional traveling wave amplifier responds appreciably only to axial electron velocities, the lens effect is able to increase the noise figure of a traveling wave amplifier. In a typical electron beam, the transverse velocity fluctuations exceed by several orders of magnitude the axial fluctuations; therefore, even a moderate transformation of transverse fluctuations into axial fluctuations results in a serious increase of noise figure.

A quantitative analysis along these lines was performed for the special case of an Einzel lens; the effect of the confining axial magnetic field was neglected. At low magnetic fields the measured increase of noisiness was found to be in excellent agreement with the values predicted by the theory. From simple considerations, it can be shown that the increase of noisiness should decrease at high confining fields, to zero at infinite field. This reduction of noise increase with increasing magnetic field was observed experimentally.

From this we have concluded that a low noise amplifier's electron gun should not be operated at electrode voltages which, because of abrupt changes in beam potential along the axis, set up strong transverse electric fields. From this point of view, large electrode apertures are highly desirable.

Low Noise Electron Gun Performance and Design

In the course of our measurements, it was possible to make an evaluation of the noise wave transforming properties of the guns used. This evaluation yielded useful design information and revealed that certain design parameters previously thought critical are not so, and the converse.

There are presently two philosophies of low noise gun design. Both of them are in essence based upon the similarity between the transformation of noise waves in an electron gun and the transformation of waves on a transmission line of non-constant impedance. The older concept, known as the "velocity jump" gun, is based upon the use of discrete drift regions alternating with jumps in beam velocity. The newer concept, originally used by Peter[10] in the first truly low noise traveling wave amplifier, is that of a smooth transformation from the potential minimum to the drift space. The transmission line analogues of the two types of transformation are a "slug tuner" and a tapered section, respectively. These principles are illustrated by Fig. 13. Both are well known, in their transmission line equivalents, to microwave engineers. It is also well known that the tapered section is the less critical of the two. The slug tuner, on the other hand, is more readily adjustable and easier to adjust to obtain a desired match.

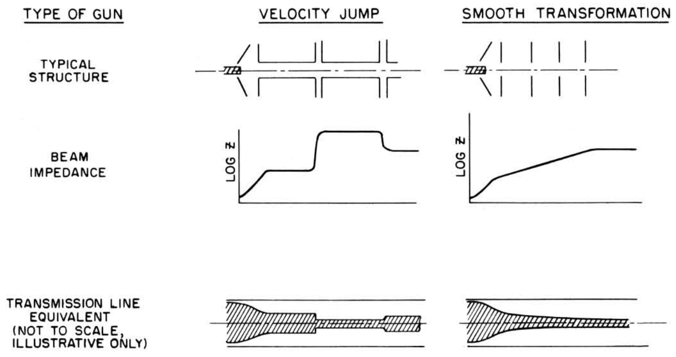


Fig. 13 – Analogues of low noise guns.

Because of the sharp potential discontinuities along the beam, unavoidable in a true "velocity jump" gun, electron guns of this type seem undesirable for very low noise operation, because of the lens effect discussed above. For this reason, we prefer the second type, characterized by a smooth space charge wave transformation between potential minimum and drift space. In practice, this transformation is obtained by the use of a number of apertured electrodes (usually three) following the first accelerating anode of the gun (Fig. 14). Because the "taper" of this transformer is rather widely adjustable by varying the individual electrode voltages, this type of gun has been found experimentally to give all the adjustability that is required in a practical tube. Furthermore, it is possible to obtain the required transformation of space charge waves with electrode potentials leading, at the worst, to very small lens effects. Fig. 15 is a Smith impedance chart representation showing the noise current standing wave ratio and the position of the standing wave as functions of the first and second anode voltages of an electron gun of the type shown in Fig. 14. It may be noted that the standing wave ratio can be varied continuously between unity and seven, and the phase shifted by more than 90 degrees by reasonable variations of the electrode voltages. The increase of the noisiness due to the electron lens effect and to variations of higher mode transformation is less than one-half db over the major part of this chart. Actually, the usual region of operation is at low standing wave ratios; as stated above, this corresponds to very small lens effects.

From this work, certain largely empirical design procedures have evolved:

1. Cathode current density for best transformation is determined by the frequency and the cathode temperature; this value corresponds to unity noise standing wave ratio at the potential minimum.
2. The gun should have at least two, preferably three, independent electrodes, to obtain sufficient adjustability.
3. The cathode-first-anode spacing should be small, since the transformation is made abrupt in this region by the space charge limited condition.
4. The anode spacings should be nearly equal; an almost lens-free transformation and adequate adjustability are produced by such spacings.
5. Anode apertures should be two to three times the beam diameter; this is a compromise between avoidance of strong lenses and obtaining sufficient independence between adjacent field regions.
6. The first anode should be operated at a voltage about 50 percent lower than that theoretically required for parallel flow (Child's law). This minimizes the abruptness of the transformation in this region. It would, in the absence of the confining magnetic field, give rise to divergence of the electron beam.

It has been observed that the exact shapes of the electrodes in the cathode-first-anode region has little effect on the noisiness of the beam, as long as the electrode apertures are sufficiently large, but has considerable effect on the noise standing wave ratio. The noisiness is also not affected by the spacings of the electrodes, so long as the fields do not produce lens effects. Because of the presence of higher order space charge wave modes, with the particular guns used the minimum noise figure was obtained with the helix rather close to the end of the electron gun. Fig. 16 shows how the noise figure is affected by the higher order modes present. The increase of the average noise figure with distance from the gun, as shown here, is attributed to these higher order modes.

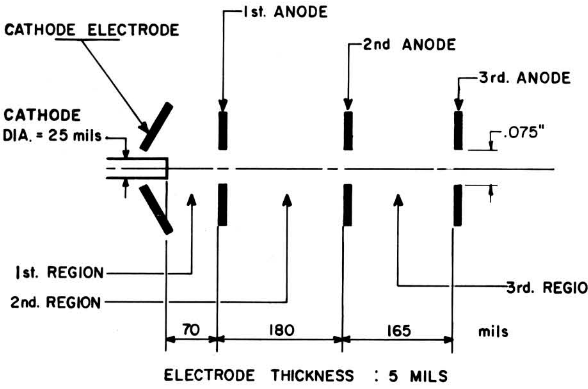


Fig. 14 – 3-region low noise gun.

Conclusions

The conclusions of the work described here are:

1. The first order theory of low noise traveling wave amplifiers has been verified by direct experiment. It was found to be valid, but only if proper allowance was made for higher order effects.

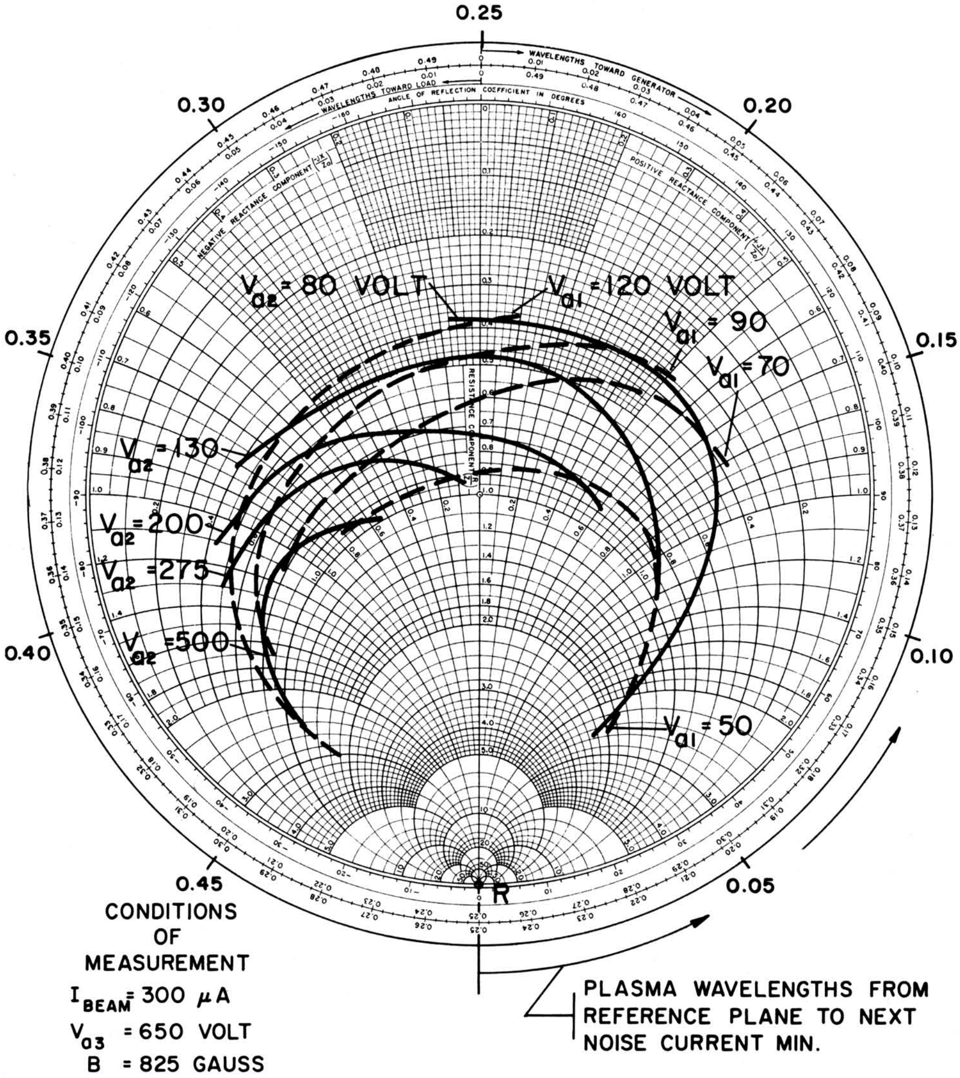


Fig. 15 – Measurement of performance of 3-region gun.

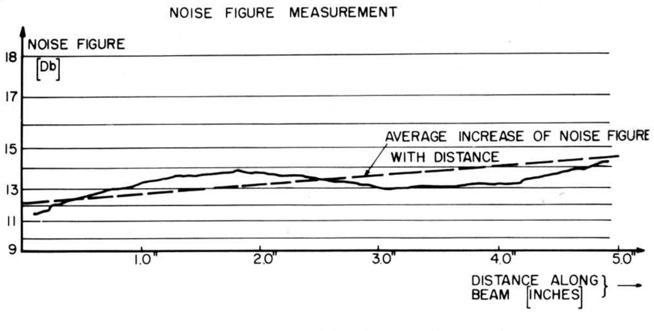


Fig. 16 – Effect of higher order modes.

2. The reduction of noise figure brought about by consideration of the geometry has been found able to account for the lowest measured noise figures. If current smoothing exists, even lower noise figures are theoretically possible.

3. Microscopic cathode non-uniformities, electron lens effects in the gun, and gas pressure have been found to be causes of the excessively high noise figure observed in some low noise traveling wave tubes. The importance of these effects has been substantiated by experiment.

4. The desirability of guns producing a smooth space charge wave transformation has been demonstrated. General directions for the design of such guns have been found.

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