RB-96

HIGH-PRECISION MEASUREMENT OF ELECTRON-BEAM NOISE

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To determine completely the noise properties of an electron beam, it is necessary to measure both the noise current and a noise figure, using the same electron beam. This involved the use of a demountable tube containing two types of rf circuits, together with ultra-sensitive detection circuits using the synchronous detection principle. In order to achieve the precision desired, the entire system was made direct reading and recording. Comparison between beam noise and a gas discharge noise standard is made continuously at the rf level, thus eliminating all error due to gain fluctuations.

Details of the demountable tube, the vacuum system, and the detecting circuits are given. Similar techniques should be applicable to other measurements of small signals or noise, and the demountable vacuum system techniques, to high-vacuum physics generally.

Introduction

The noise figure[1] of a microwave beam amplifier is intimately connected with the fluctuations in current and electron velocity of its beam. Present theories[2,3] indicate that the noise properties of an electron beam should to first-order approximation be measurable in terms of either the noise *current* in the beam (which can be measured by a resonant cavity) or the noise *figure* performance of the beam in an rf amplification circuit of known characteristics. By making measurements of *both* quantities with the *same* electron beam, it is possible 1) to verify the correctness of the theory, 2) to establish the basic noise properties of the particular beam, 3) to determine noise transformation properties of specific types of electron guns, and 4) to search for higher-order effects which may alter the validity of first-order noise figure theories. These measurements have been discussed elsewhere.[4,5,6,7,8]. Without the precision of the system to be described, it is doubtful that some of these results could have been achieved.

A review of the difficulties attending such noise current and noise figure measurements may be helpful. The type of data which are needed are plots of noise current or noise figure vs. the distance from the electron gun to the noise-measuring cavity, or to the input end of the (noise figure measuring) rf circuit. This means that either the cathode and electron gun, or else the rf circuits, must be moved during or between measurements. The desire for continuous measurement necessitates a movable bellows, or else sliding vacuum seals; practically speaking, a continuously-pumped vacuum system is necessary. Pressure must be maintained at 10^{-7} mm Hg or better, to assure no electron-molecule collision problems.

The noise-current measurement itself is made difficult by the smallness of the noise power coupled from the beam to the (gridless) resonant cavity. In this case this noise power is, at its greatest, about 10 db below the thermal (Johnson) noise power of the cavity itself. Since microwave receivers in the S-band region, where these measurements were made, have noise figures of the order of 10 db, direct detection of the noise is not possible. A synchronous detection principle similar to that of the Dicke radiometer[9] must be used. As described later, Dicke's circuit was modified appreciably in order to obtain continuous comparison with a noise standard.

The noise-figure measurement is difficult only in the sense that continuous recording of the data was desired, whereas the usual method[10] involves a two-step measuring process. A circuit was devised, using most of the elements of the noise current circuit, whereby accurate and continuous noise-figure plots could be obtained.

Specific problems in the various elements of the system are discussed in the sections following.

Noise Current Measuring System

The conventional Dicke radiometer utilizes the circuit shown schematically in Fig. 1. The input from the unknown noise source is fed to a rotating attenuator, which modulates the noise at 30 cps. The unknown noise 'signal' then enters a superheterodyne receiver, which is followed by a high-gain narrow-band audio amplifier. If the system is linear, only the unknown (input) noise is modulated, at the rate determined by the rotating attenuator It follows from the narrow bandwidth of the tuned amplifier that this modulated signal is amplified, while all signals at other frequencies are neglected. By use of a phase discriminating detector, all signals other than the unknown are then completely eliminated from the detected output.

The measurement of electron-beam noise current involves the thermal noise of the resonant cavity, since the beam is not very tightly coupled to the cavity. Accordingly it was found more advantageous to square-wave modulate the beam, and thereby eliminate need for the rotating attenuator. Since the cavity's thermal noise is *not* square-wave modulated, it does not contribute to the signal in the tuned audio amplifier. Another difficulty of the Dicke system is thereby eliminated, for unless Dicke's rotating attenuator is perfectly matched at all positions, it may introduce a time-varying mismatch and thereby a spuriously-modulated local oscillator signal to the receiver.

Measurements made with a high-sensitivity radiometer may be subject to error because of amplifier gain variations. Only by using a noise standard at the input, in place of the unknown, can the measurement be checked. Initial experiments indicated that gain fluctuations were excessively large to allow use of this method of calibration, therefore a continuous calibration system was devised.

The system as finally developed is shown schematically in Fig. 2. By using oppositely-phased square-wave modulation on the beam and on the noise standard, and by properly adjusting the attenuator, it is possible to cause the noise power delivered to the cavity by the beam to equal the noise power delivered to the cavity by the noise source. Under these conditions, the rf output from the cavity to the microwave receiver has *no* modulation at the synchronous frequency (in this case 75 cps). The cavity acts as both rf beam current detector and filter for the (broadband) reference noise. Since adjustment of the attenuator to equal the two noise components produces a modulation-free noise signal at the receiver input, the output of the phase-sensitive detector is likewise zero. If the beam noise exceeds the reference noise, or vice versa, an unbalance signal appears at the output of the phase sensitive detector. This voltage is then employed as an input to a servo amplifier which controls a motor driving the attenuator. The amplifier acts only as a nulling amplifier, hence the attenuator position at balance does not depend on amplifier gain. This characteristic is the outstanding feature of this system. If comparison were made between the beam noise signal and a reference at a point elsewhere than in the rf circuit, amplifier gain would be a determining factor.

Since the noise source cannot be a primary standard of electron beam noise, a full shot noise current in the beam (obtained as described later) is used to calibrate the beam noise. Unless the rf connections are changed about, it is not necessary to recalibrate between measurements.

The attenuator setting is now a measure of the beam noise current and is recorded on one axis of an X-Y recorder, from a precision potentiometer attached to the attenuator. Another potentiometer, attached to the rf assembly drive mechanism, indicates the position of the rf circuit on the other recorder axis. Voltage for driving the relay circuits is obtained from a synchronous motor-generator system, pictured in Fig. 3. Two ac 'rate generators' are connected by a non-slip rubber belt to a

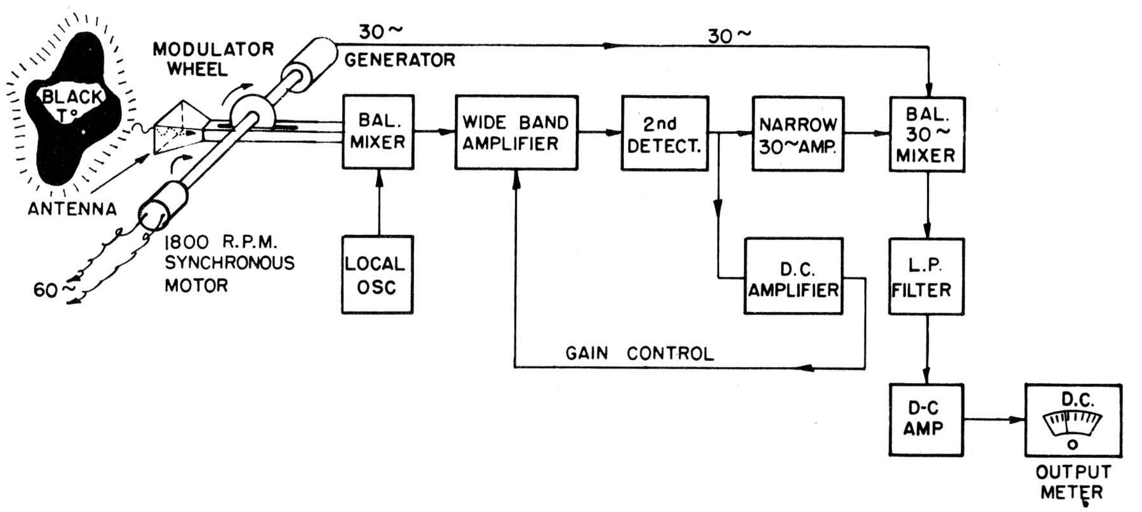


Fig. 1 – Dicke microwave radiometer.

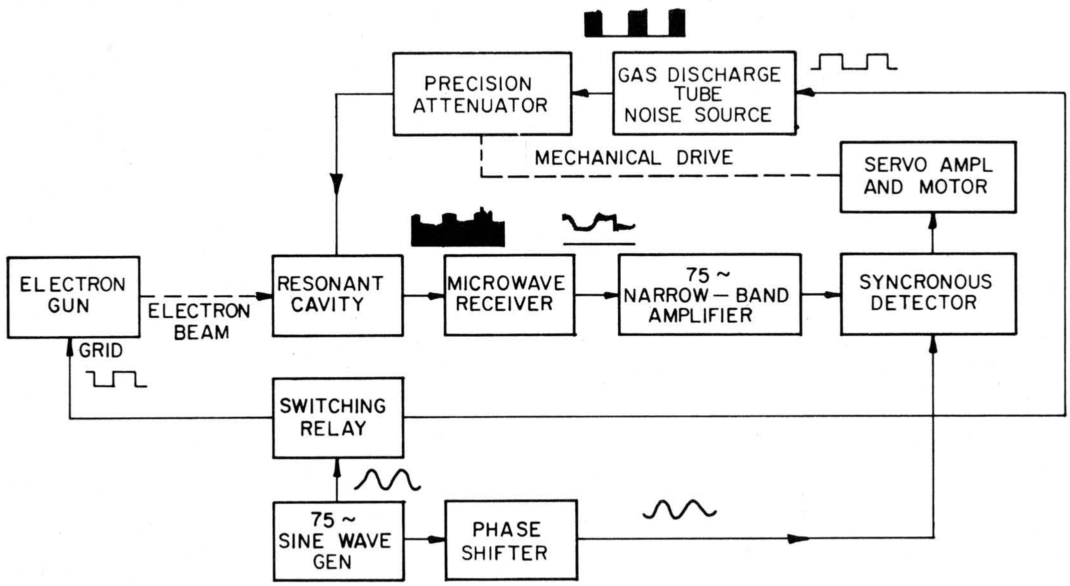


Fig. 2 – Block diagram, noise current measuring apparatus.

synchronous 60 cps motor. Relative phase is controlled by moving one of the generators, in its mounting, with respect to the other.

The high-gain tuned amplifier circuit used is almost identical to that described by Roess.[11] The only major difference is the addition of a push-pull vibrator demodulator using two Western Electric type 726-E mercury-wetted relays. The modified circuit diagram is given in Fig. 4. Details of the input stage operation, which is very important for high sensitivity, may be obtained from the Roess paper.

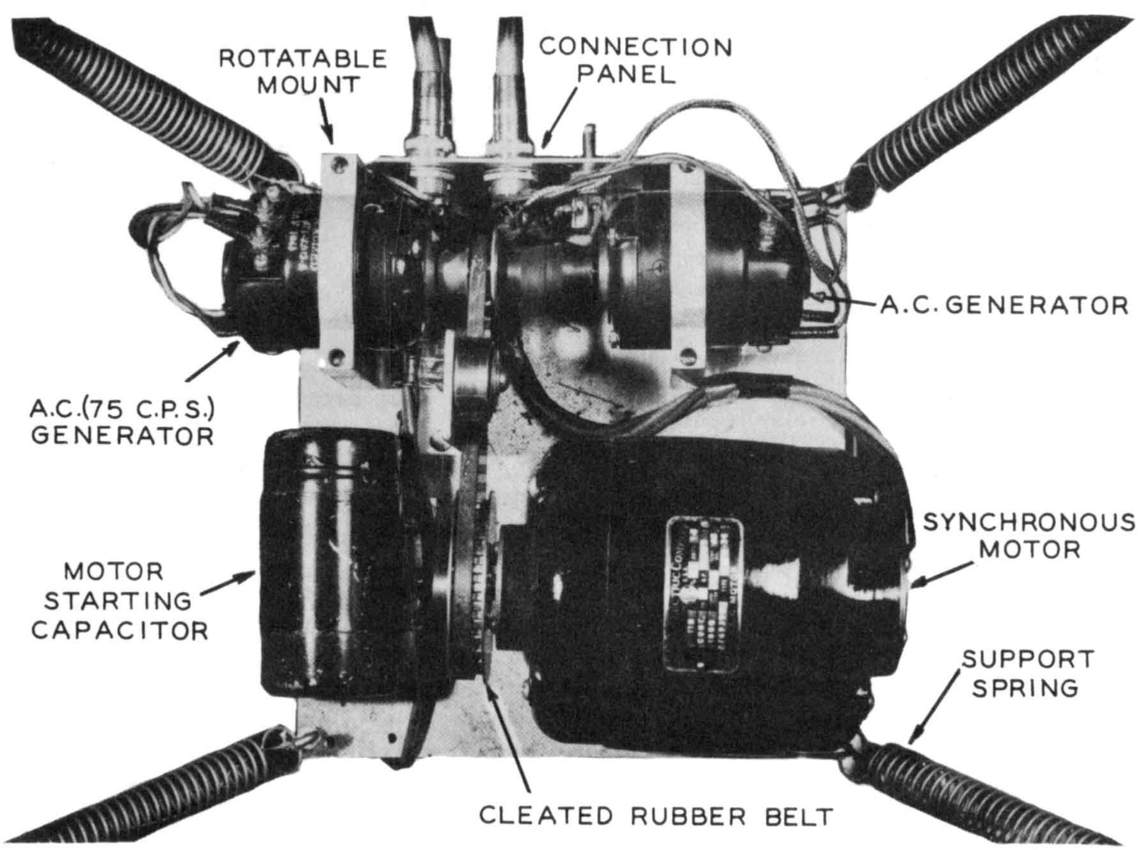


Fig. 3 – Synchronizing motor-generator.

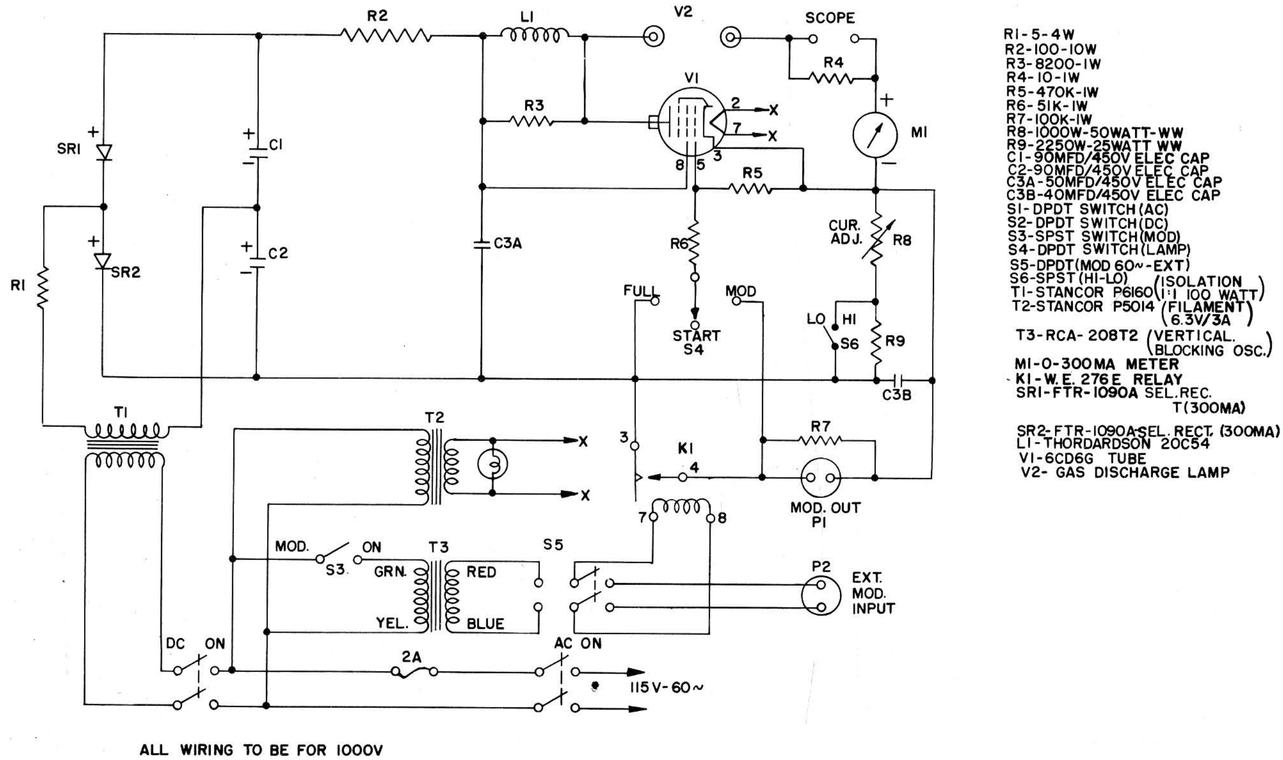


Fig. 5 – Schematic-modulator and power supply microwave noise source.

Noise Source and Beam Modulator*

The circuit which supplied power to the noise reference source and modulation to the electron beam is shown in Fig. 5. Because the gas discharge noise source requires high ignition voltage, electronic circuitry is required to square-wave modulate the discharge current. A 75-cps current from one of the rate generators operates relay K_1 at a 75 cps rate. When the relay closes, with switch S_4 in *MOD* position, the grid of V_1 is driven hard negative. This cuts off V_1 abruptly, and since at this point the noise source tube is not conducting, a high-voltage pulse appears across inductance L_1, igniting the noise-source discharge. When the relay opens 1/150 second later, the grid of V_1 is allowed to return to cathode potential, which causes V_1 to draw sufficient current through R8 and R9 to extinguish the discharge. The voltage that is applied to the grid of V_1 also appears at the *MOD OUT* plug P_1 and is used to control the electron beam of the demountable tube. This assures phase synchronization between noise source and electron beam.

This noise-source modulator is also a useful general-purpose power source for gas discharge noise tubes. Currents of from 50 to 250 ma are available, and any such noise-source tube may be started under cold-cathode conditions. Because the circuit is isolated from the chassis, it may be employed (through P_1) to modulate a cathode-grid circuit not at ground potential; in the present apparatus, this circuit drives the electron gun, modulating the beam under test.

*This circuit has been described by W. R. Beam and R. D. Hughes in *TRANSACTIONS of the P.G.E.D., IRE,* April, 1957.

Noise Figure and Gain Measurements

It seemed desirable to be able to record noise *figure* with the same accuracy and degree of automation; fortunately, only a small addition was needed to enable the noise-current apparatus to perform this function, with automatic gain measurement thrown in as a bonus. The principle of the noise-figure measurement is shown in block form in Fig. 6. The noise source, square-wave modulated, feeds into the input of the amplifier through a servo-driven attenuator. The receiver is a superheterodyne, as before. The output of the second detector (in this case, a crystal) appears across a tapped load resistance, with the adjustable tap nominally set to 50 percent. A synchronously-driven relay connects the high-gain amplifier to the *tap* when the noise source is *on,* and to the *full* detector output when the noise source is off. The electron beam is unmodulated. Assuming the second detector to be square-law, its output voltage will double

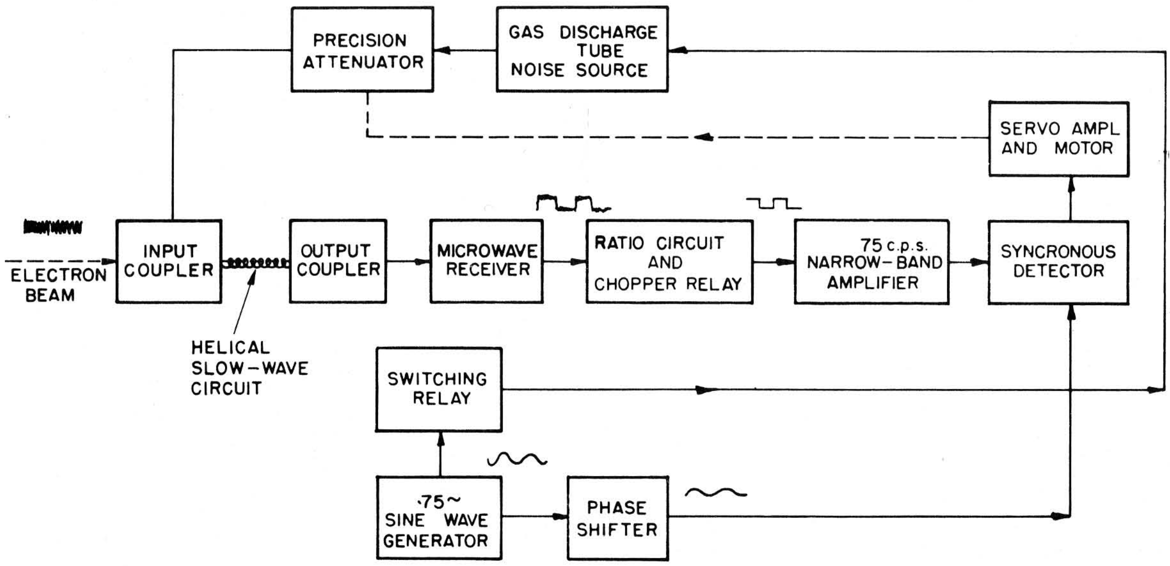


Fig. 6 – Block diagram, noise figure measuring system.

if the input *power* doubles. If the power out of the traveling-wave amplifier is twice as great when the noise source is *on* as when it is *off*, the 75 cps input to the tuned amplifier from the relay is zero. This two-to-one power ratio is a convenient condition for noise-figure measurement[10]. The attenuator is adjusted to this condition by the servo system, just as in the noise current measurement; noise figure, consequently, is proportional to attenuator reading at balance.

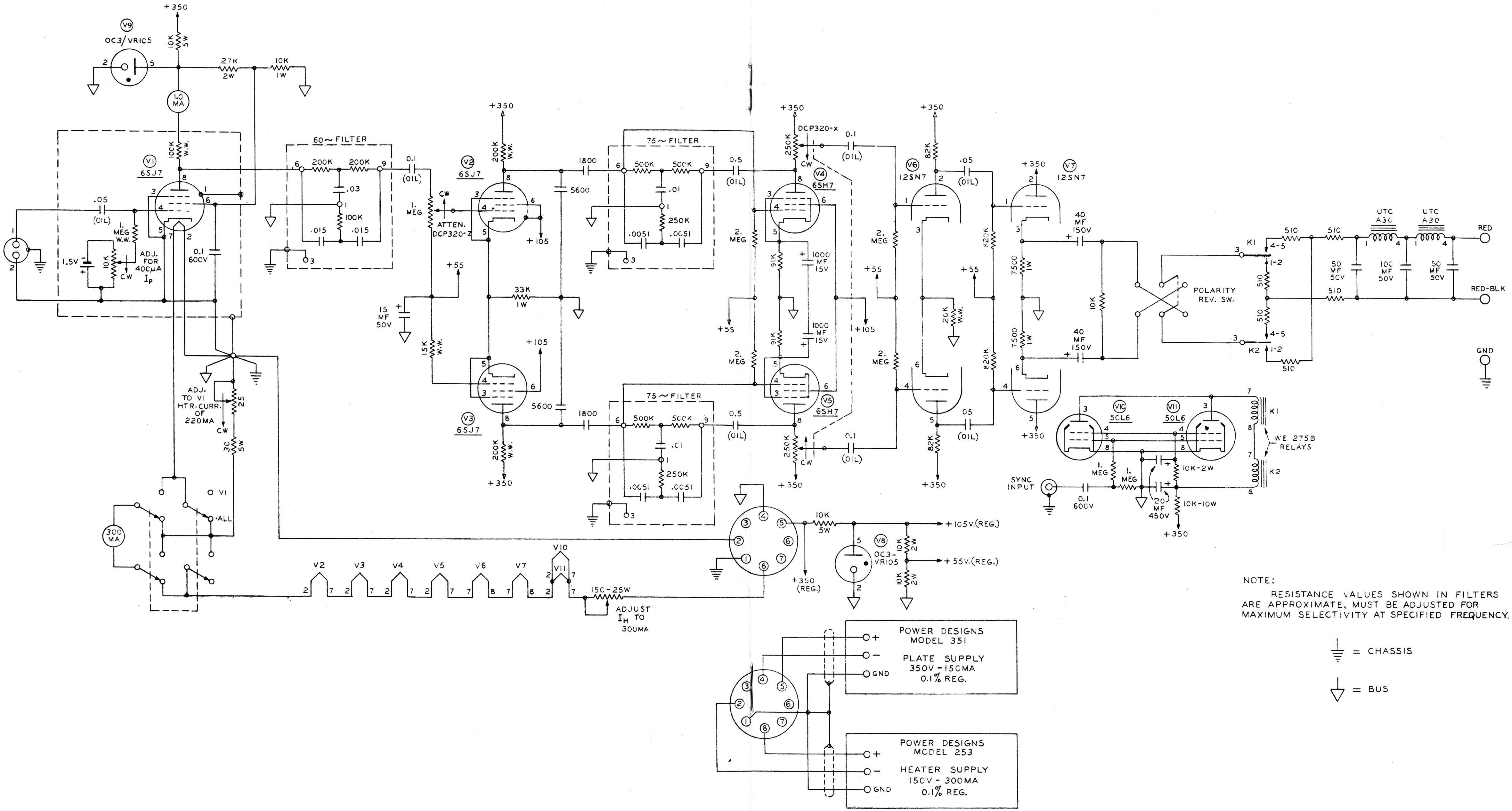
The additional circuit required is shown in Fig. 7. In addition to the relay circuit described, it contains an agc circuit to keep the detector operating at constant level, independent of the gain of the helix and beam. This circuit compares the detector output when the noise source is *on* with a fixed reference voltage. A high-gain amplifier and a double-diode phase-sensitive detector supply an automatic bias to the if strip. The circuit will maintain essentially constant input to the detector over an approximately 80-db range of if input.

Because the crystal second detector is *not* truly square law, the detector load tap may need to be set slightly off 50 percent, if the system is to indicate true noise figure. An auxiliary vacuum tube (6AL5) detector with accurately known square-law range is supplied for making manual measurement of noise figure. The tap on the detector load is then simply adjusted to make the automatic indication agree with the manual reading. Monitoring jacks are provided in both the relay circuit and the agc circuit; oscilloscope observation is useful in adjusting the phase of the synchronizing voltage and in verifying correct operation. When the function switch in the circuit of Fig. 7 is switched to the 'noisiness' position, the relay and agc circuits are disconnected and beam noise current in a cavity may be measured as described previously. In the 'noise figure' position operation is as described above. A third position, 'gain', connects the agc circuit directly to the servo-driven attenuator. It automatically adjusts the *input* signal into the traveling-wave amplifier from a signal generator to such a level that the detected output exactly equals the agc reference level. In this function the noise-source tube is not used, the purpose being to measure the gain of an amplifier in the rf circuit. The difference in attenuator setting caused by switching the traveling-wave amplifier in and out of the circuit is the amplifier gain.

The automatic noise-figure measuring circuit, in addition to its usefulness in specific work, is advantageous for general noise-figure measurements. It enables electrode voltages and beam current to be varied, while the operator observes noise figure continuously on the servo-driven attenuator. Accurate optimization of tube adjustments may be made in a minimum of time. While it is somewhat more complex than some other automatic noise-figure systems, it offers the advantage that the power ratio (noise-source-on to noise-source-off) is 2 to 1, for all noise figures. If, however, the tube noise figure should be so large that this power ratio cannot be reached, the detector load tap may be readjusted to such a position, for example, that 3 db (or any other desired factor) must be added to the indicated noise figure (in db.)

Demountable Vacuum Tube and System

The requirements of the demountable tube in which noise current and noisiness of an electron beam are


+350
V9
OC3/VR105
10K 5W
27K 2W
10K 1W
1.0 MA
10K W.W.
V1
6SJ7
.05 (OIL)
1. MEG W.W.
1.5V
10K
CW
ADJ. FOR 400μA I_P
0.1 600V
60~ FILTER
200K
200K
.03
100K
.015
.015
0.1 (OIL)
1. MEG
CW
ATTEN. DCP320-Z
V2
6SJ7
200K W.W.
5600
1800
+105
+55
15 MF 50V
15K W.W.
33K 1W
V3
6SJ7
75~ FILTER
500K
500K
.01
250K
.0051
.0051
0.5 (OIL)
DCP320-X
0.1 (OIL)
250K
CW
V4
6SH7
V5
6SH7
2. MEG
91K
1000 MF 15V
+55
+105
V6
12SN7
82K
.05 (OIL)
2. MEG
20K W.W.
V7
12SN7
620K
7500
40 MF 150V
10K
POLARITY REV. SW.
K1
K2
4-5
1-2
510
UTC A30
50 MF 50V
100 MF 50V
RED
RED-BLK
GND
ADJ. TO V1 HTR. CURR. OF 220MA
25
30 5W
V1
ALL
300 MA
V2 V3 V4 V5 V6 V7 V10 V11
150-25W
ADJUST I_H TO 300MA
+105V.(REG.)
+55V.(REG.)
+350 (REG.)
V8
OC3-VR105
10K 2W
SYNC INPUT
0.1 600V
1. MEG
20 MF 450V
10K-2W
10K-10W
V10
V11
50L6
WE 275B RELAYS
POWER DESIGNS MODEL 351
PLATE SUPPLY 350V - 150MA 0.1% REG.
POWER DESIGNS MODEL 253
HEATER SUPPLY 150V - 300MA 0.1% REG.
GND
NOTE:
RESISTANCE VALUES SHOWN IN FILTERS ARE APPROXIMATE, MUST BE ADJUSTED FOR MAXIMUM SELECTIVITY AT SPECIFIED FREQUENCY.
= CHASSIS
= BUS

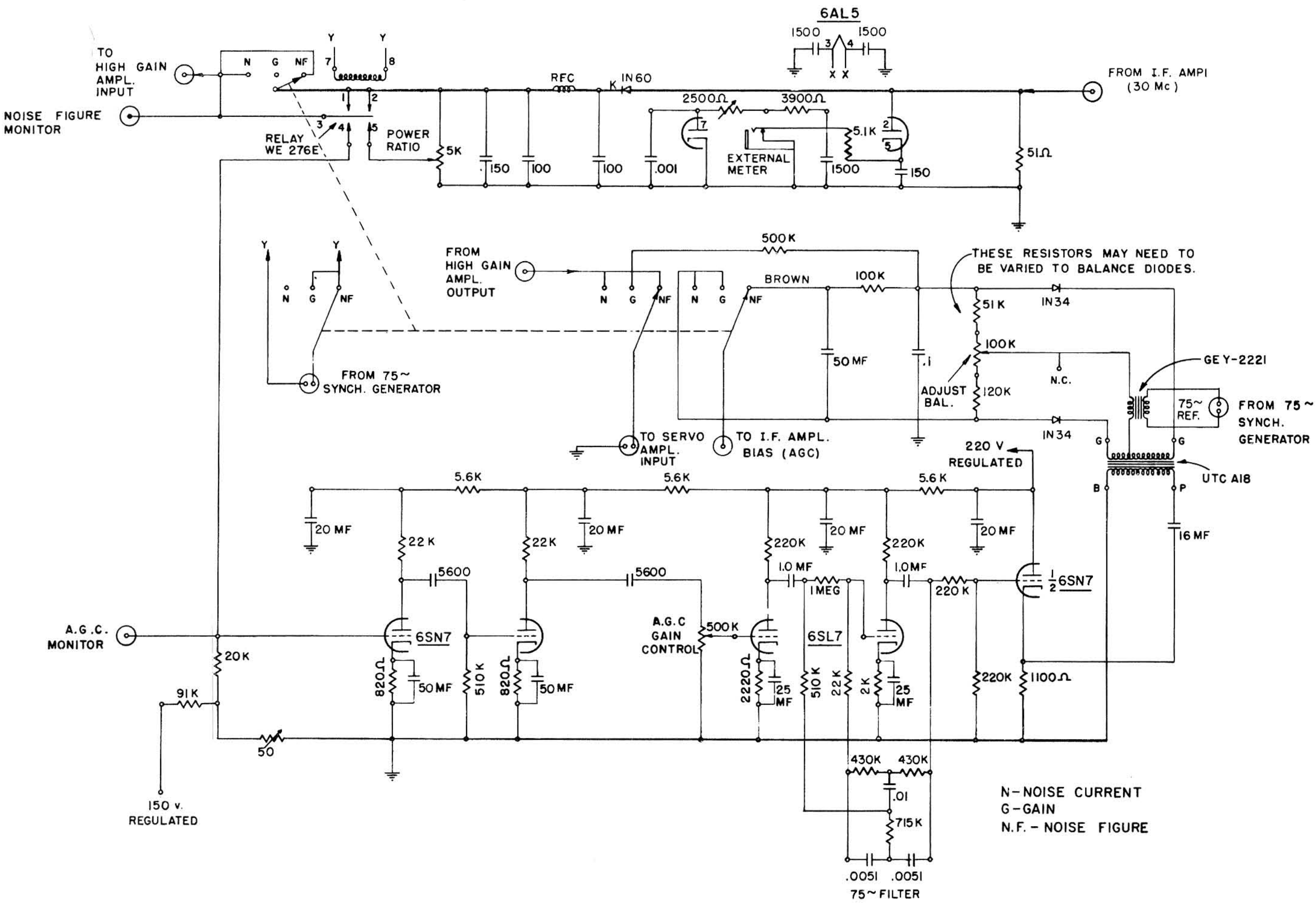


Fig. 7 — Schematic of noise current-gain-noise figure circuit.

measured are: 1) a precisely positioned mount for the electron gun; 2) a resonant cavity and a helix, with two rf connections to each; 3) provisions for moving the cavity and helix with respect to the electron gun, or the converse, together with the necessary vacuum seals or bellows for accommodating the change in length; 4) means for maintaining a vacuum at least as low as 10^{-7} mm Hg. In addition to these major requirements there are more subtle ones, such as means for enclosing the beam while it drifts on its way from the gun to the cavity and helix, a magnetic focusing field of sufficient uniformity over the entire length of the tube and of sufficient field strength to confine properly the electron beam, and, very important, a vacuum and supporting structure which will align all of the parts while providing some degree of visibility of the inner parts.

The basis of the demountable tube and vacuum system was a system built previously by one of the authors[12]. The liquid nitrogen trap, of 2-liter capacity, has a cylindrical opening through which the electron gun is inserted into the demountable tube, from the rear. In operation, the cathode is no more than four inches from the nearest surface of the trap. Despite the large number of O-rings and rubber gaskets, all 'hidden' from the vacuum by metal flanges, etc., the system is capable of attaining a pressure of 2×10^{-8} mm Hg, after a few days of pumping. The pumping speed of the Edwards oil diffusion pump (with baffle valve) is approximately 200 l/sec. Liquid nitrogen capacity of the cold trap is two liters, sufficient to last about 8 hours between fillings. The system has been operated continuously for as long as 1500 hours, without deterioration of the vacuum.

The demountable tube (pictured in Fig. 9) employs a precision-bored brass tube as the main structural member. The brass tube has large rectangular holes cut in both sides, which allows the internal mechanism to be assembled, operated, and inspected before slipping on the outer glass tube which serves as the vacuum envelope. The use of a tube as the structural member rather than an assemblage of rods or other type of supporting structure was found necessary because for given dimensions a tube has greatest strength; the tube is cantilivered from the vacuum system. The internal assembly fits this tube with a clearance of five mils or less. In operation, the

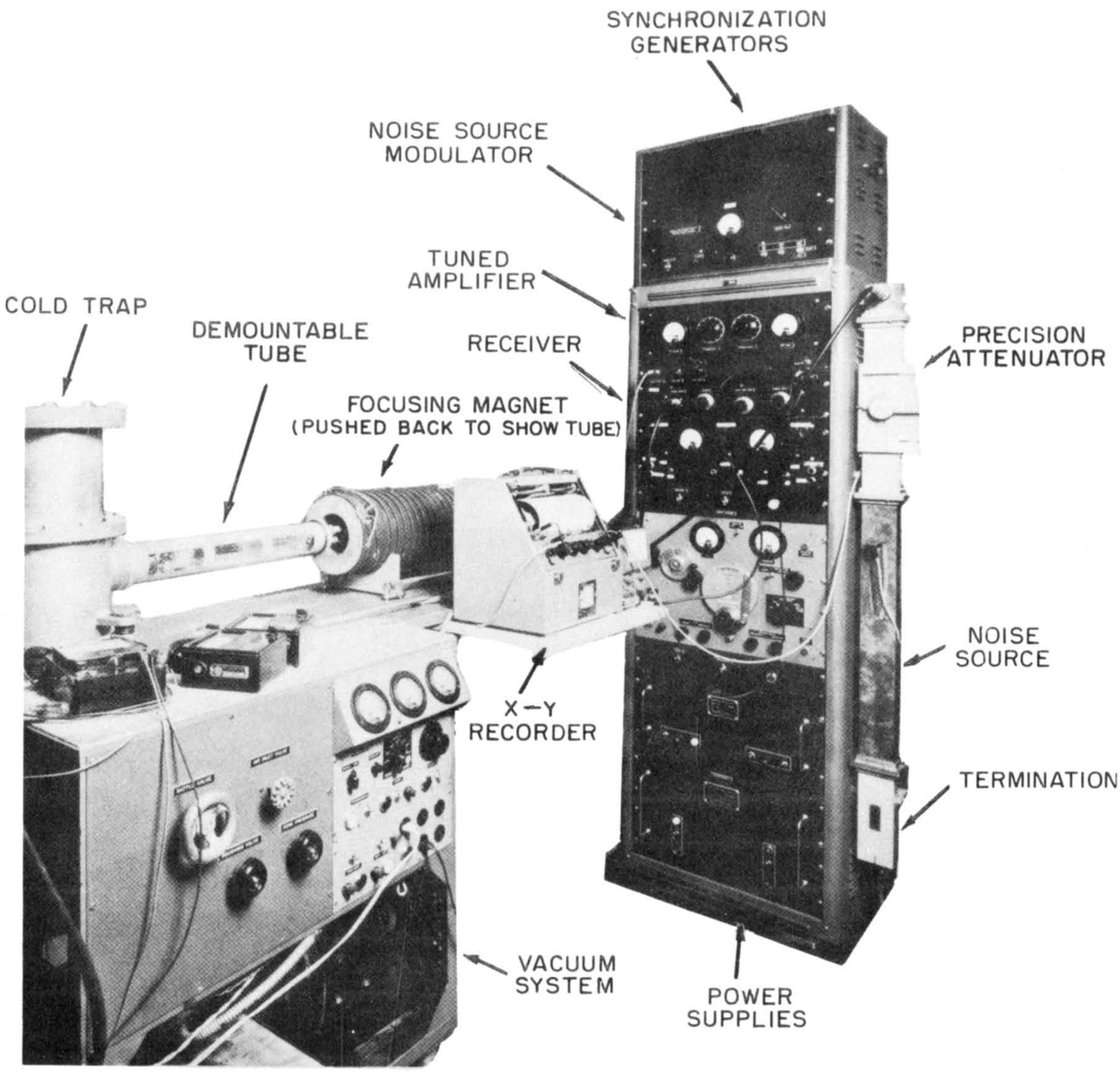


Fig. 8 — Noise measuring system.

movement of the rf assembly through the tube follows an essentially straightline path; this is tested by the variation of intercepted current as the rf assembly is moved back and forth.*

The moving rf assembly, shown in Fig. 10, consists of a resonant cavity and a cavity-coupled helix, with four brass tubes carrying RG 58/u coaxial cables to the outside. Hermetic glass-to-metal seals at the vacuum end of the coaxial lines prevent possible gas evolution from the polyethylene insulation. The rf couplings to cavity and helix were adjusted at the desired operating frequency; there was no attempt to broad-band the helix match, although as built it was satisfactory over a range of perhaps 50 mcs near 3000 mcs.

The rf assembly is moved back and forth in the tube by an external variable speed drive. Although data may be taken when moving the rf assembly in either direction, measurements are normally made only when pulling the lines out through the vacuum seals because: 1) the tube being cantilivered from the vacuum system, any off-axis force developed in pushing in the assembly will represent a sidewise thrust and can deflect the tube; since the assembly is pulled out by means of a bead chain, no such deflection can occur in pulling out; 2) in pushing the assembly, it must be moved very slowly to prevent what gas is absorbed on the coaxial lines from evolving within the high vacuum region.

To prevent vacuum leakage while the cavity and helix were moved, it was found necessary to use *double* O-ring seals, with a fore-pressure connection in the

*The writers feel that an even better support would consist of a relatively weak internal system of rods, supporting and spacing the internal mechanism and providing a base for its assembly, with a precision bore glass tube acting as both the vacuum envelope and the main structural member. This is practical today because of the great accuracy and low cost of precision shrunk glass tubing.

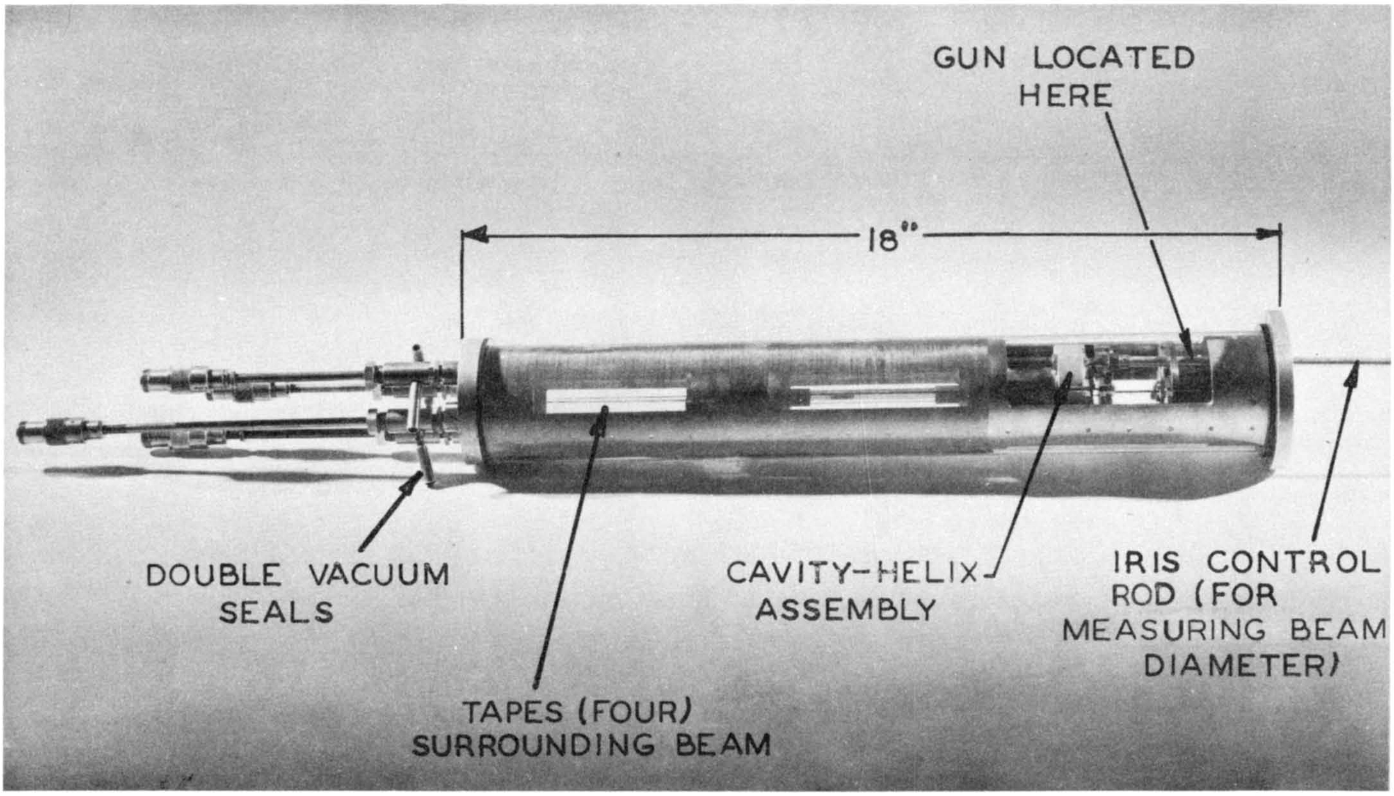


Fig. 9 – Demountable noise measuring tube (removed from vacuum system).

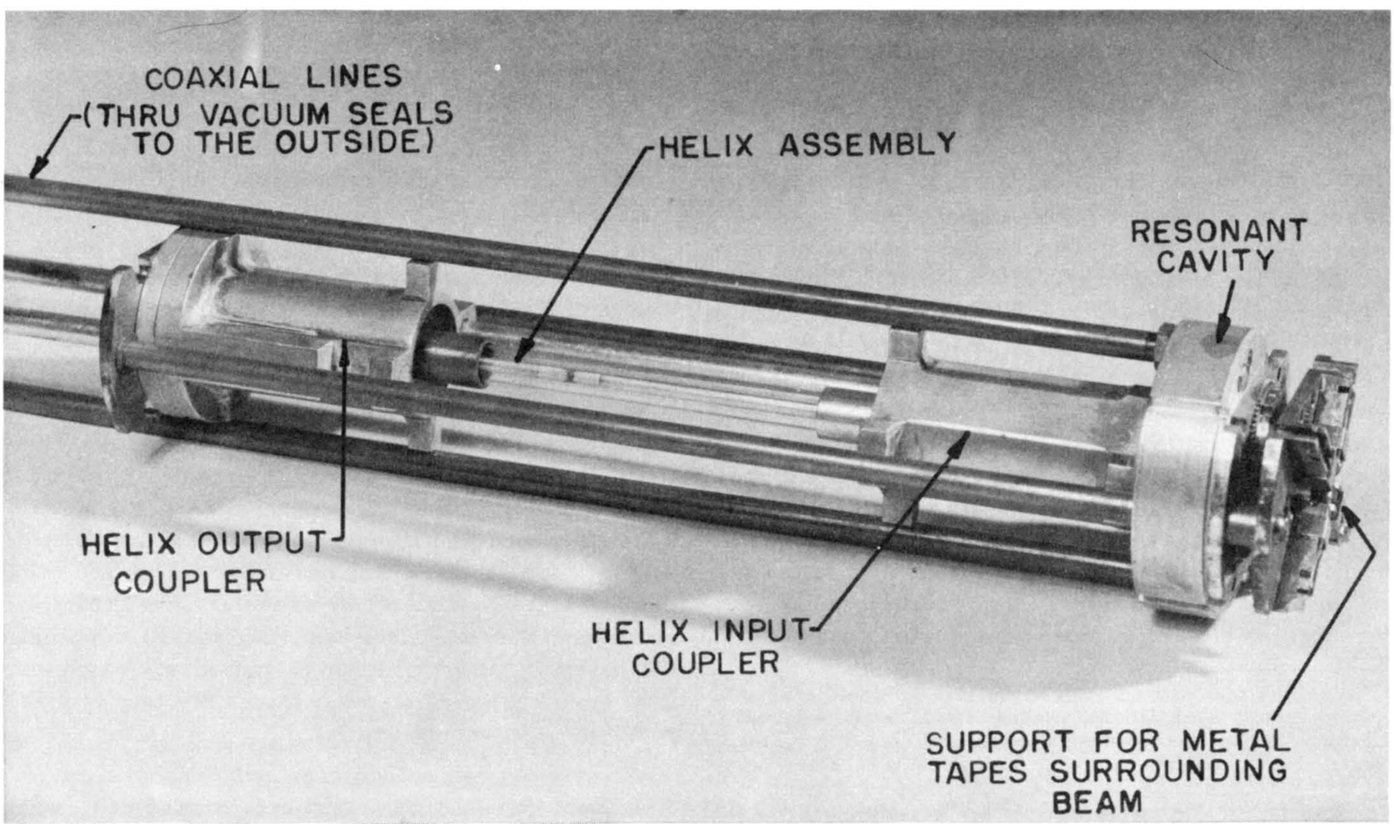


Fig. 10 – Movable cavity-helix assembly.

intervening region. The simple arrangement shown in Fig. 11 has been found to operate satisfactorily; no leaks are indicated by either the ion gage or the cathode (the emission current of which is a very sensitive indicator for tiny oxygen leaks).

Not shown in detail in the illustrations is the beam size measuring iris, which consists of a plate in which a number of holes have been drilled: one of the holes is covered with a fine, low-transmission (1%) mesh, which is used to produce a known shot-noise current. The iris plate is positioned by means of a detent, through a geared control shaft extending outside the vacuum. By mounting the gear on the control shaft with some peripheral play, the detent on the iris plate can (audibly) jump into position without being retarded by the friction in the vacuum seal.

The focusing magnet is a large, iron-shell, water-cooled solenoid capable of continuous operation at fields up to 1000 gauss. It rests on a spring-balanced cradle, which allows a variety of adjustments: the springs take most of the magnet weight off the adjusting screws. The cradle is mounted on ball-bearing wheels and rolls on a track atop the vacuum system. It is simple, therefore, to back the magnet away from the demountable tube in order to make pyrometric measurements of cathode temperature, or to observe the position or operation of internal parts.

Operation of the Complete System

As with any complicated system involving continuous vacuum pumping and rf measurements, taking of data on this system is something of a project. The electron gun is mounted into the tube, with diffusion pump hot (but baffle valve shut) and cold trap at room temperature. Rough-pumping with the fore-pump to a pressure of about 10 microns takes about 15 minutes. After 'roughing', liquid nitrogen is poured into the cold trap, then the baffle valve is opened. Pressure immediately falls to about 5×10^{-7} mm Hg, and as the walls clean up, reaches about 4×10^{-8} mm Hg within 24 hours; final indicated pressure has been as low as 1.0×10^{-8} mm Hg. The cathode is activated only when the pressure has fallen below 10^{-7} mm Hg. Activation procedure is generally based on time and temperature; because of the high pumping speed of the system, the evolution of gases does not produce noticeable increase of system pressure. Outgassing of tube parts is also no problem if the demountable system has been carefully cleaned with acetone and dried, after any assembly procedures in which it may have become contaminated.

Alignment of the tube and magnet is carried out by interception measurements. The hole in the resonant cavity is of 0.080-inch diameter: with 0.030-inch diameter electron beams of 300 microamperes current, little difficulty is experienced in passing 99.7-percent of the beam current all the way to the collector at magnetic fields of 550 gauss or more.

The noise current and noise figure are recorded directly on the x-y recorder. The first noise-current data taken on each sheet is usually a shot noise calibration, which, although not essential, is a guarantee that the system is performing correctly. Since the low-transmission grid on the iris plate (which is permanently mounted before the cavity) has exactly 1 percent transmission, a run of noise current vs. distance from gun to cavity gives a calibration curve exactly 20 db below full shot noise; constancy of this level indicates that beam alignment within the cavity hole is good. The noise

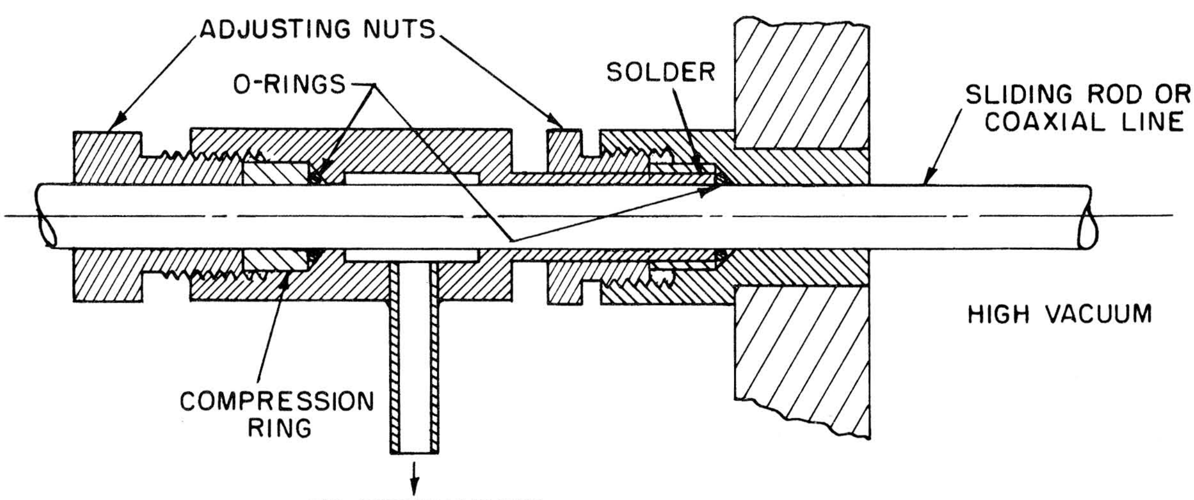
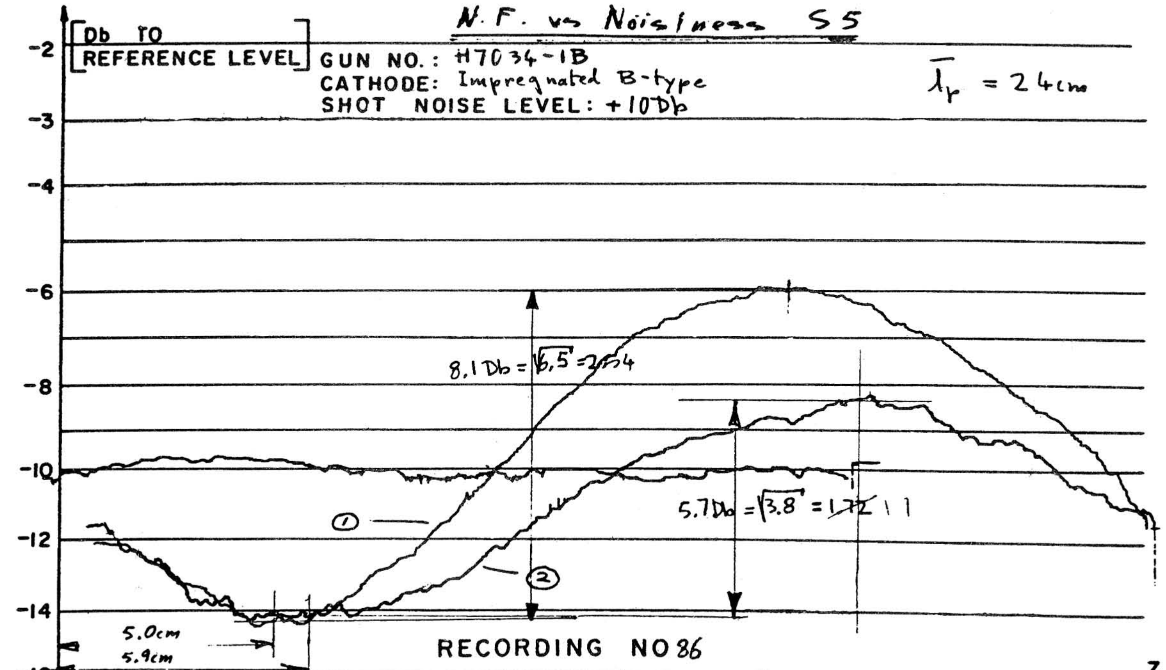
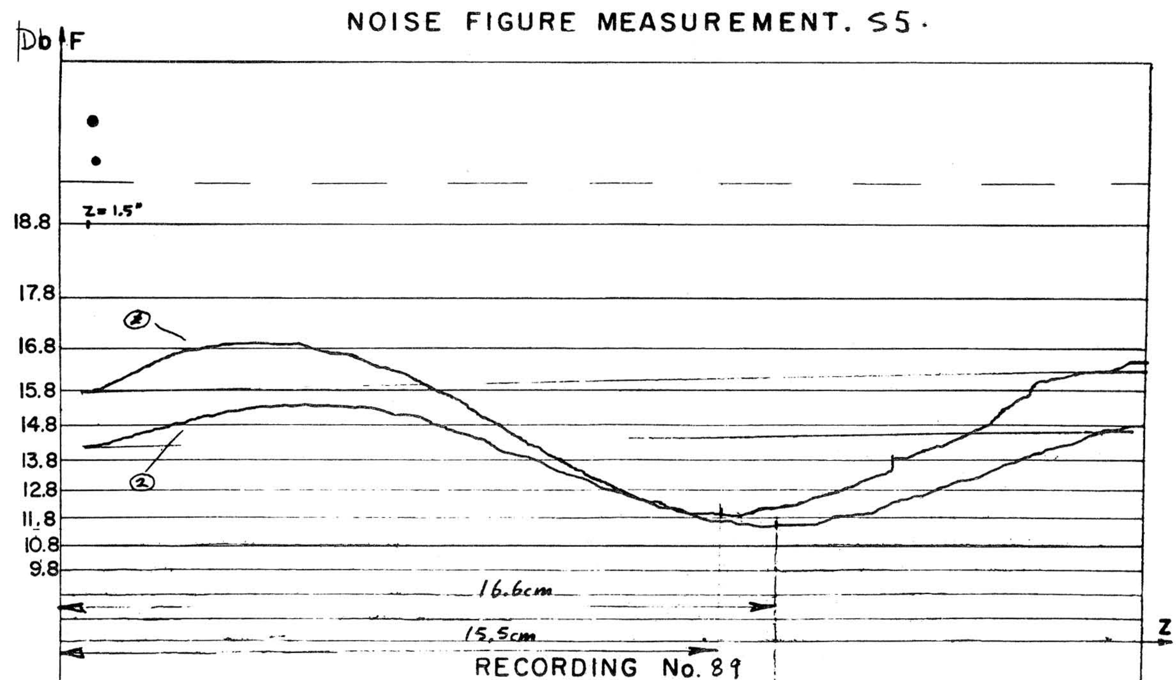


Fig. 11 – Double O-ring sliding seal for demountable vacuum system.



CURVE NO.	V_{G-1}	V_{a1}	V_{a2}	V_{a3}	V_H	$\hat{I}_{COLL}$	I_{HEAT}	B_{GAUSS}	I_H	V_{a+}	$\lambda_{p\,cm}$	Φ	η	N
1	0	51	80	500	650	300	3.2	825	< 1 μA	650	24	37.5	2.54	20.2
2	0	50	130	"	"	"	"	"	< μA	650	25.5	44.3	1.72	21.3

Fig. 12a – Unretouched reproduction of noise-current measurement.



CURVE No	V_{G-1}	V_{a1}	V_{a2}	V_{a3}	V_H	$\hat{I}_{COLL}$	I_H	I_f	B_{GAUSS}	C POT.	$\phi°$	F_n	F_t	η
1	0	52	80	500	650	300	< 1 mA [redacted]	3.2	825	240	169	16.9	11.5	2.54
2	0	51	100	500	650	300	< 1 mA [redacted]	3.2	825	240	178	14.2	11.2	2.38

Fig. 12b – Unretouched reproduction of noise-figure measurement.

current vs distance curve may then be taken. A typical result is shown in Fig. 12a. The fine structure is due to the fact that the receiver has a short response time, and therefore picks up *fluctuations* in the beam noise power. With a response time of about one second the fluctuations amount to about one-half decibel, but these may obviously be averaged out.

Noise-figure measurements are made in much the same way, except that no useful initial calibration can be made. A typical curve (matching the noise current curve of Fig. 12a) is shown in Fig. 12b. It will be noted that, with the scale used, data can be read to within 0.1 db. Repeatability of the system over a period of one month has been found to be better than 0.2 db. Since both types of measurements are actually comparisons of tube noise with the noise of a gas discharge tube, the noise source itself may be blamed for a large part of any repeatability error. Another possible source of error (but one of little consequence) is the balance of the synchronous detectors in the system. These detectors should have zero output when the input is in quadrature with the reference signal, or when the input is zero. If the diodes or choppers become unbalanced, however, they may put out a residual signal when the input is actually nulled. This must be checked every few days by oscilloscopic observation of the relative phases of the various 75-cps voltages in the system, and by checking that detector output is zero, with zero input. Since the system is a nulling system, and has a large amount of gain, the effect of an unbalance in the detector is relatively small.

The gain of the system, when used to measure noise current, must be greater than that for noise *figure* measurements, because in the latter there is additional gain due to traveling-wave amplification. The available gain in this system is such that the system will measure noise current equivalent to full shot noise in a beam of only 0.5 microampere, with the stated accuracy of 0.1 db. This lower limit of measurable noise current is dependent on how accurately the detectors are balanced, and how long a time constant is tolerable.

Conclusions

The apparatus described in this bulletin was constructed to enable certain fundamental noise measurements to be made. Previous measurements of this type had been made manually on a point-by-point basis, but with the system described, continuous measurements were made in a time so short that drift and change of cathode properties were not important; this system is the first in which noise current and noise figure measurements can be made on the same electron beam. The continuous data revealed several interesting and unexpected effects, which had previously gone unnoticed and unexplained.

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