Velocity-sorting detection in backward-wave autodyne reception

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RADIO AND ELECTRICAL ENGINEERING DIVISION

VELOCITY - SORTING DETECTION IN BACKWARD - WAVE AUTODYNE RECEPTION

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OTTAWA

APRIL 1960

ABSTRACT

Possible application of a retarding-field velocity-sorting process to detection in a microwave receiver was investigated. The receiver consisted of a double-ended backward-wave oscillator operating as an autodyne. Operating parameters of the receiver such as dynamic range, electronic tuning, stability, and sensitivity were measured and the results compared with those obtained from a similar autodyne receiver using an external crystal detector. It was found that the velocity-sorting detector is equal to the crystal type in sensitivity and nearly equal in dynamic range, but inferior in gain stability. The poor gain stability is due to the variation of detection efficiency with beam current, which is inherent in a retarding-field detector.

CONTENTS

FIGURES

PLATES

VELOCITY-SORTING DETECTION IN BACKWARD-WAVE AUTODYNE RECEPTION

- J.K. Pulfer -

INTRODUCTION

There are many applications in the field of microwave measurements for a simple, sensitive, electronically tunable receiver. An unconventional receiver consisting of an oscillating backward-wave amplifier in a microwave autodyne circuit has been described previously [1]. A block diagram of this receiver is given in Fig. 1. Briefly its mechanism of operation is as follows.

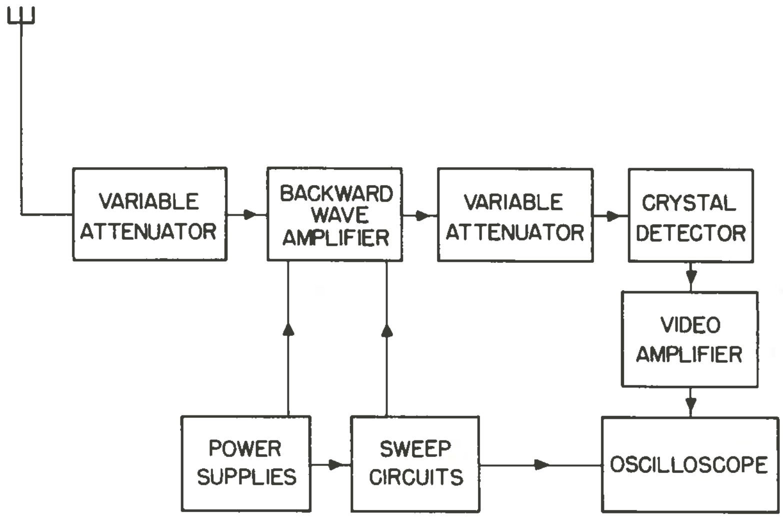


FIG. 1 BLOCK DIAGRAM OF A BACKWARD-WAVE AUTODYNE SWEPT RECEIVER

The tube, which is a helix-type backward-wave oscillator modified by addition of an input transition at the collector end of the helix, is operated at a beam current slightly higher than that necessary to sustain oscillations. The applied signal travels down the helix, and since it is of the same order of magnitude as the oscillation itself, is amplified greatly, and adds to the oscillation, so that the radio-frequency output at the gun end of the helix is modulated by the difference frequency. This radio-frequency output is detected in a conventional waveguide crystal mount, and fed to a video amplifier.

This receiver has a large dynamic range and high rejection of unwanted frequencies. It is, therefore, well suited for spectrum analysis of a signal which covers a large percentage bandwidth. However, the output voltage variation with signal frequency is dependent on the crystal mount and it is very difficult to find a crystal and mount combination in which detection efficiency is independent of frequency. Further investigations were made to find out whether or not the video signal could be recovered directly from the electron beam by means of a suitable collector.

COLLECTOR DETECTION

The electron beam at the output of the helix of a backward-wave tube which is oscillating will, in general, have both velocity and current modulation. At the beam current for maximum sensitivity, i.e., when the oscillator output voltage is of the same order as the amplified signal voltage, the velocity and current modulation on the electron beam vary in amplitude at the beat frequency. Any means of detecting variations in beam velocity distribution or variations in beam current distribution would, therefore, serve as a signal detector.

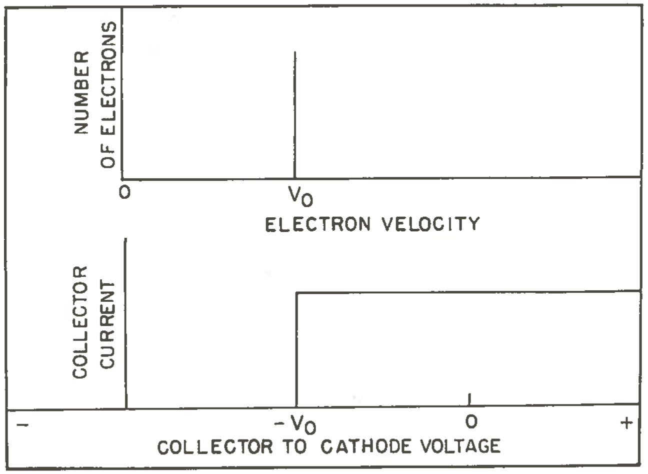
A collector biased negatively with respect to the helix of the tube decelerates electrons. The collector current is, therefore, made up of the electrons which have sufficient energy to overcome the repelling field of the collector; i.e., all the electrons having more than a chosen velocity. Such retarding-field velocity-sorting detectors have been used in many applications [2, 3].

To predict the behaviour of the electron current arriving at the collector as various parameters are changed, we will begin with an oversimplified model and then correct for the simplifications one at a time.

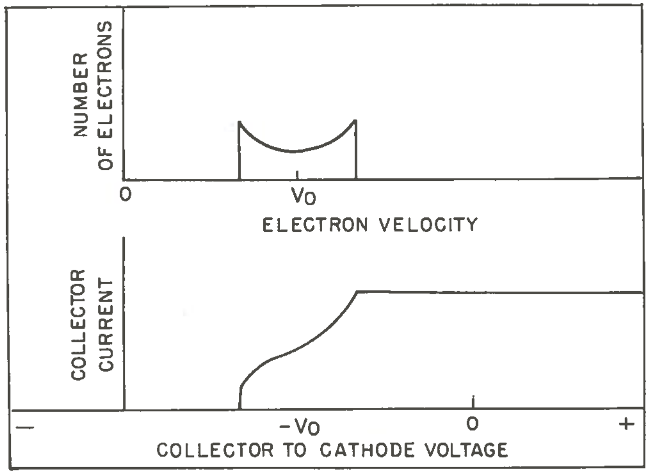
First, assume that the electron beam has only axial components of velocity, that all of the electrons arrive at the collector without being influenced by transverse fields, and that all the electrons have the same initial axial velocity (V_o volts) on leaving the cathode. Further, assume that any electrons which are repelled by the collector, return to the cathode and do not influence the beam in any way. Space charge is neglected for the present. Fig. 2 is a series of composite drawings showing idealized velocity distributions for the electron beam after it has been decelerated to cathode potential, and the corresponding variation of collector current with collector voltage.

Fig. 2(a) is a plot of collector current versus collector voltage for the idealized case. There are two possibilities: either all of the electrons are accepted by the collector, or none of them.

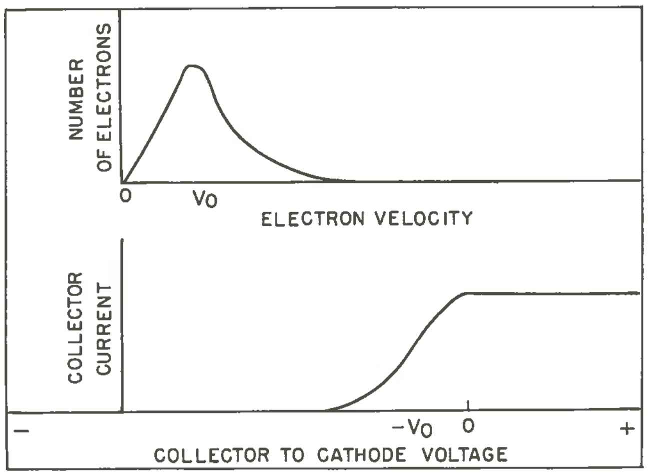
Suppose now that the electron beam were to be velocity-modulated with a small sinusoidal signal. The distribution in velocity of electrons which have left the helix and have been decelerated to cathode voltage (neglecting space charge effects) would be the sinusoidal distribution shown in Fig. 2(b). The collector current at any chosen collector voltage would be proportional to the integral from 0 to V_c of the velocity distribution. This is also illustrated in Fig. 2(b) in the lower curve. It will be noted that in comparison with Fig. 2(a), collector current is larger in Fig. 2(b) at values of collector voltage V_c less than V_o, but is smaller when V_c



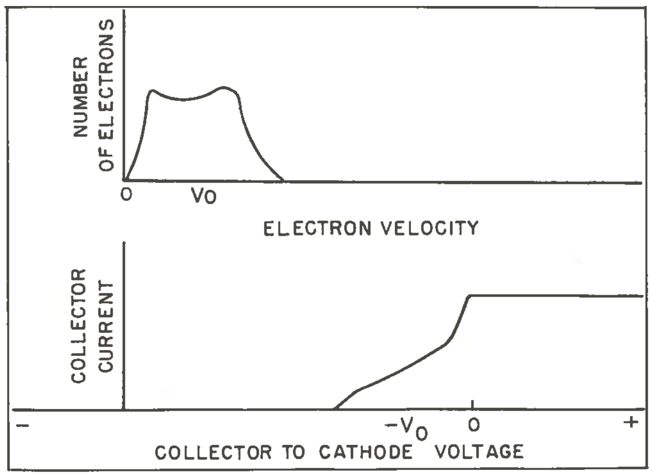
a) Univelocity electron beam



b) Univelocity beam of electrons velocity-modulated by a sine wave



c) Electron beam with a Maxwell velocity distribution



d) Electron beam with a Maxwell velocity distribution modulated by a sine wave

FIG. 2 PLOT OF ELECTRON VELOCITY DISTRIBUTION AND RESULTANT COLLECTOR CURRENT CHARACTERISTICS is greater than V_0. A collector at a voltage slightly greater than, or less than V_0 could detect the presence of sinusoidal modulations on the electron beam by this change in collector current.

Suppose that the collector voltage is set for optimum detection of small signals. Because of the shape of the amplitude distribution function for a sinusoid, collector current will increase rapidly for small amounts of modulation, and then increase more slowly for larger modulation. As a result, the output-input characteristic of the collector detector is non-linear. Any saturation of the beam by large signals will add further to this non-linearity.

Now, consider a more complicated model in which the axial velocities of all the electrons in a beam are not equal, but are distributed about an average value with a distribution which approaches the Maxwell distribution. This is illustrated qualitatively in Fig. 2(c) which may be compared with (a) and (b) for the delta and sinusoidal distributions.

Finally, if an electron beam with an initial Maxwell velocity distribution is modulated with a sinusoidal signal, then the new velocity distribution will be "spread out" as shown in Fig. 2(d). As a result, the collector current will also be changed, as illustrated.

Consider now some of the other factors affecting the number and velocity of electrons reaching the collector.

The Varian VAD-161* series backward-wave oscillator tubes which were used in the experimental receivers have a positive grid or accelerating anode between the cathode and the input of the helix. The hollow electron beam from the grid is passed through a "beam shaver" to reduce its diameter to the inside diameter of the helix. There is also some unavoidable interception of electrons by the helix itself. As a result, current injected into the collector region is only a small fraction of cathode current. The body, helix, and beam shaver, are all at the same potential.

Another important factor is the development of a space charge cloud or virtual cathode in the decelerating region. The establishment of the virtual cathode reduces the current reaching the collector and makes it a function of beam current as well as beam velocity [4, 5]. Fig. 3 is a three-dimensional graph giving the calculated value of collector current as a function of collector voltage and beam current. The curves are based on a model with electrons injected perpendicularly to a set of plane parallel electrodes at a single velocity [6]. The spacing between

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* These tubes were developed by Varian of Canada Ltd., Georgetown, Ont., under the auspices of the Defence Research Board, Canada (Electronic Components Research and Development Committee).

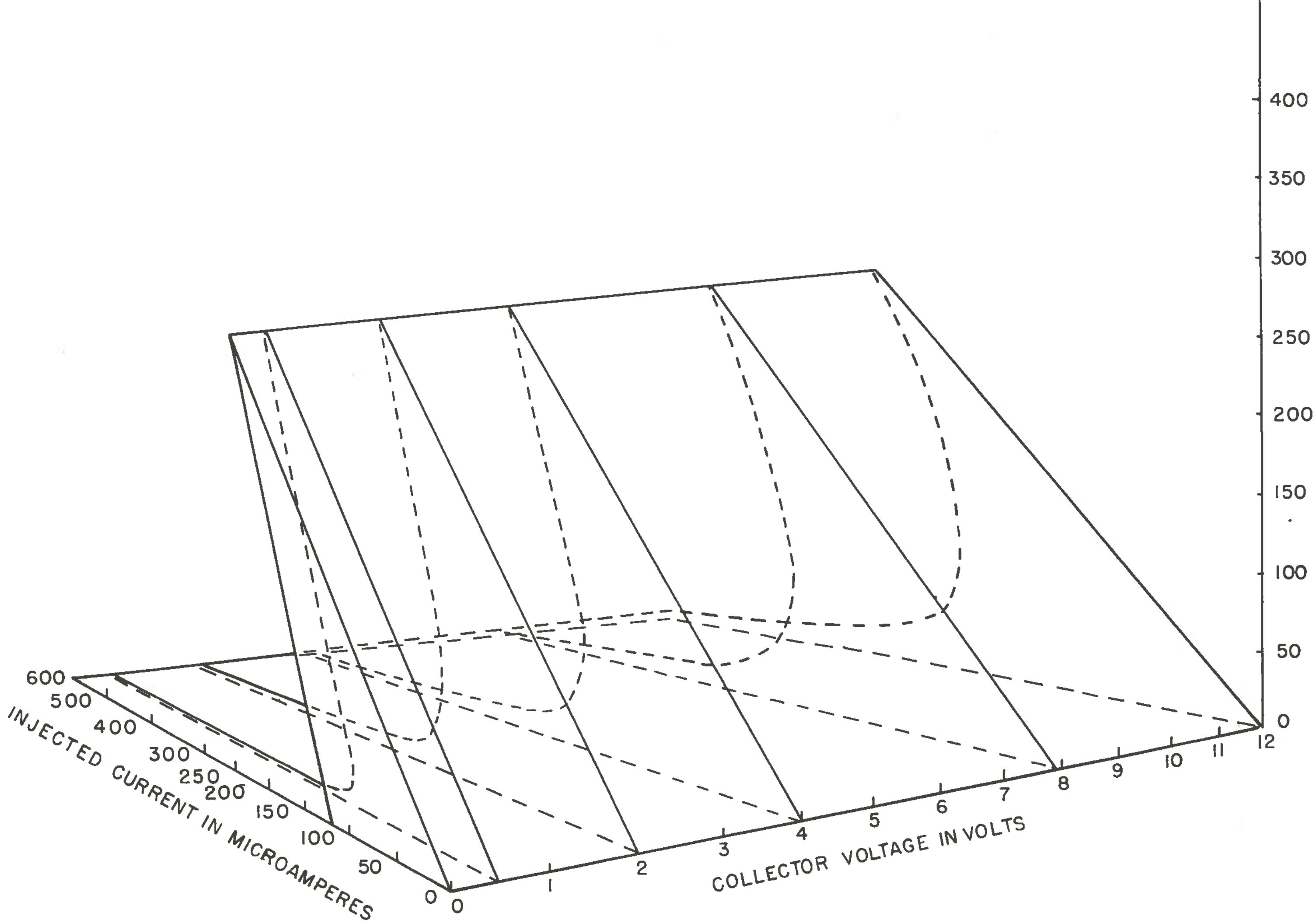

FIG. 3 THREE-DIMENSIONAL GRAPH OF THEORETICAL COLLECTOR CURRENT FOR HELIX VOLTAGE 200 VOLTS, DECELERATION GAP WIDTH .015 INCHES

electrodes, and voltage between them, have been chosen approximately equal to those in the backward-wave oscillator collector region.

There are three regions of interest. For low beam current, collector current is linearly proportional to beam current, and independent of collector voltage. For this region, no virtual cathode exists, and no electrons are turned back at the potential minimum. For high beam current, collector current increases with collector to cathode voltage and decreases with increasing beam current. In this region a virtual cathode exists and a fraction of the electrons are returned to the cathode.

There is an intermediate region in which either of the above states can exist. Whether or not there is a virtual cathode in the center region depends on which way the region is approached.

RESULTS

To obtain a better understanding of the mechanism of collector detection in backward-wave tubes, experimental data on collector current versus collector voltage were taken. Two different tubes were used for the measurements. The first was the Varian type VAD-161-2. The collector was not designed for depressed operation. When collector potential was lowered to within a few volts of the cathode, a virtual cathode was formed near the collector.

Fig. 4 is an expanded scale drawing of a cross section through the collector for the Varian type VAD-161-2 tube. The collector doubles as part of the pole piece in this tube. The outer part of the pole piece is at helix potential. In the absence of negative voltage on the collector relative to the helix, the beam will follow the magnetic lines to the collector. When collector potential is reduced towards cathode potential, it would be expected that a virtual cathode would develop, returning a fraction of the electrons to the body and to the helix.

A three-dimensional graph of collector current versus collector voltage for the type VAD-161-2 tube, when the collector is very nearly at cathode potential, is presented in Fig. 5.

The existence of the virtual cathode in the type VAD-161-2 tube resulted in oscillations when a load resistor was connected to the collector, so that signal detection with this tube was very difficult.

Fig. 6 is a drawing of the type VAD-161-4 tube. In this tube the outer part of the pole piece is also at collector potential. Since the area of the collector is larger, the magnetic focussing field strength in the collector region is somewhat less. When the collector is negative with respect to the body, a strong electric

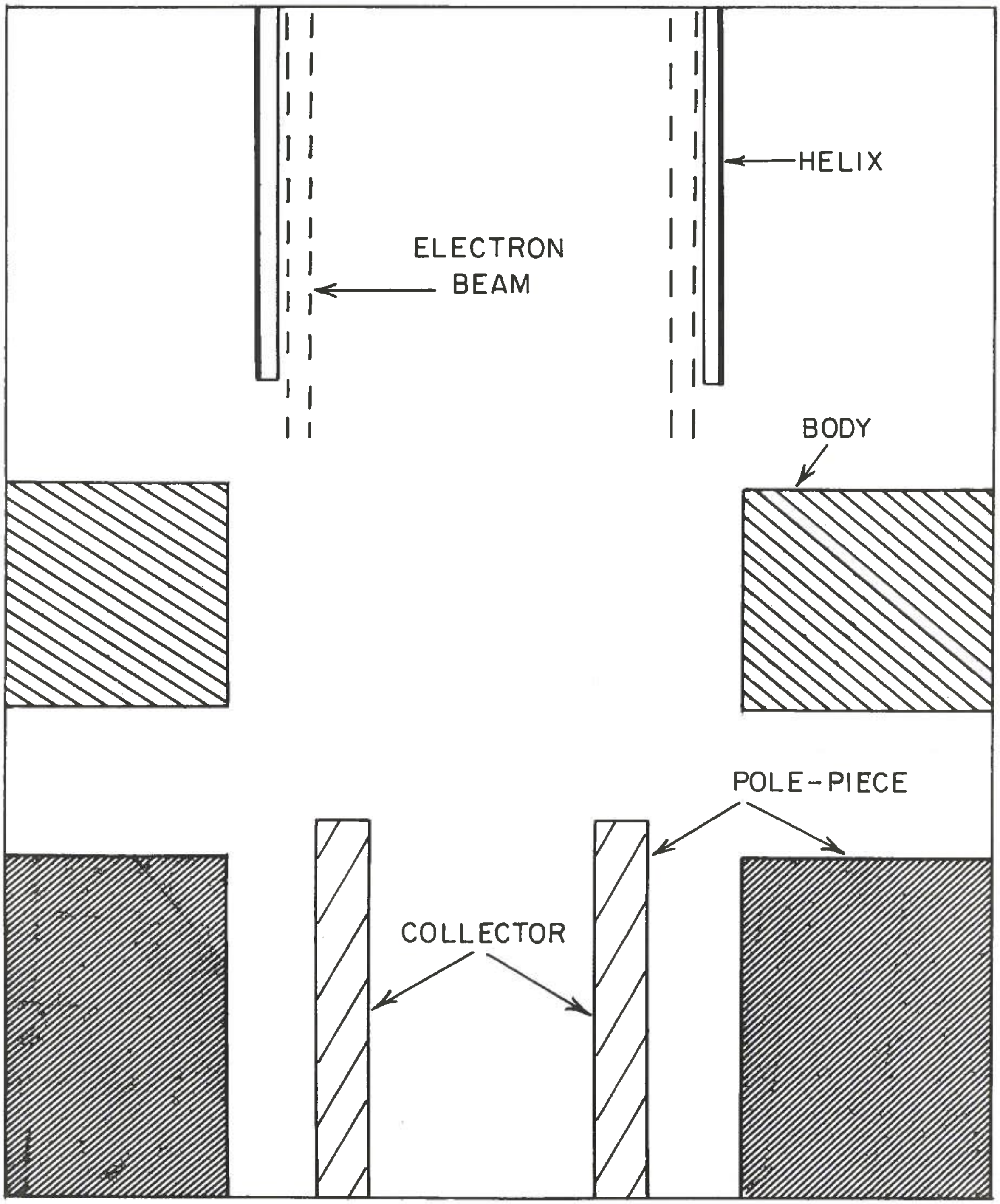

FIG. 4 CROSS SECTION THROUGH COLLECTOR REGION OF VARIAN TYPE VAD-161-2 TUBE

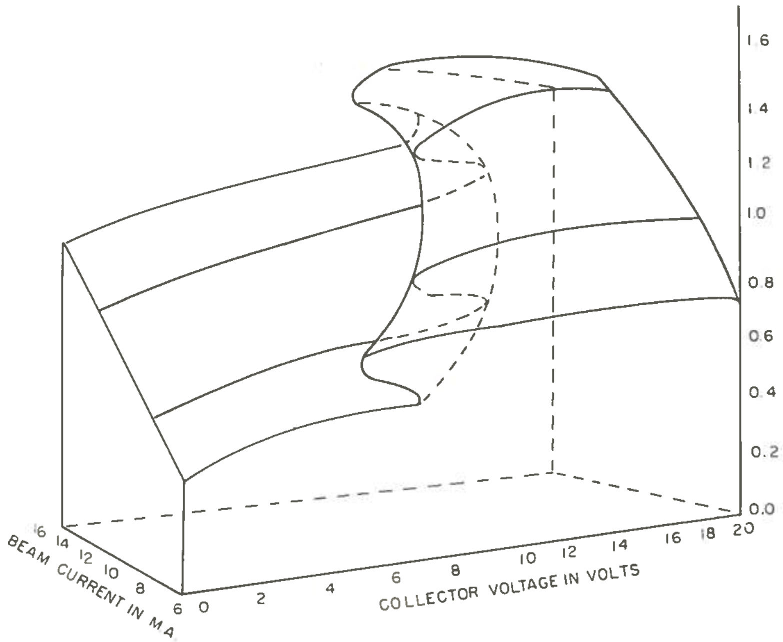

FIG. 5 THREE-DIMENSIONAL GRAPH OF MEASURED COLLECTOR CURRENT FOR TYPE VAD-161-2 TUBE

field directed radially exists, which will tend to force the electron beam outward. Therefore, when electrons are decelerated (since the focussing force exerted by the magnetic field in the collector region is small) they will be swept outward, and be collected by the body, and a virtual cathode cannot form.

With the type VAD-161-4 tube, no instability was observed at any value of collector voltage, beam current, or beam velocity.

Plates I and II show a three-dimensional plot of collector current for the type VAD-161-4 tube. Collector current below oscillation starting current increases with both beam current and collector voltage. This indicates that no virtual cathode exists, but that electrons are being transferred radially outward to the body from the beam, as explained earlier.

At the start of oscillation (a beam current of about 3.5 ma) there is an abrupt change in collector current. At low collector voltages the collector current rises at the oscillation starting point, as was predicted from a simplified analysis neglecting space charge effects. Note, however, that the drop of beam current at high collector voltages is much steeper than the rise at lower voltages. This occurs because, when beam velocity is spread by the presence of backward-wave oscillation, more electrons are decelerated than are accelerated.

Measurements were made with the collector of the tube serving as a detector.

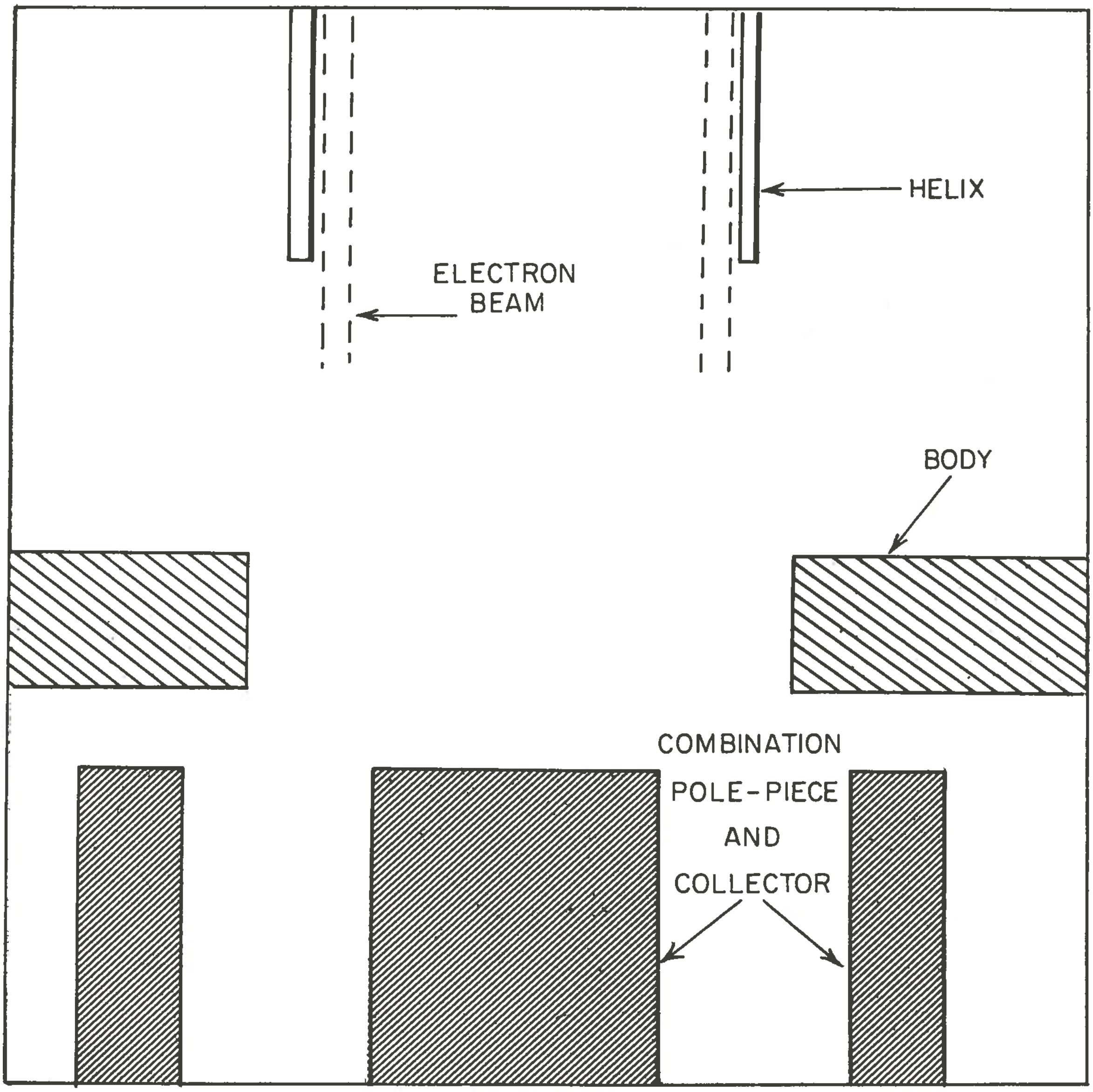

FIG. 6 CROSS SECTION THROUGH COLLECTOR REGION OF VARIAN TYPE VAD-161-4 TUBE

The circuit used is shown in Fig. 7. Provision was made for detection by crystal as well as by collector.

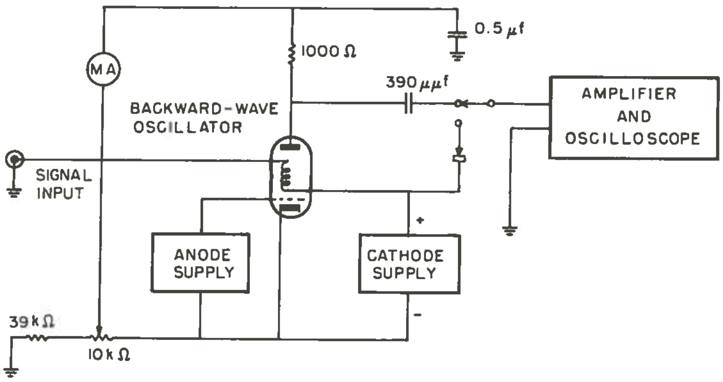

FIG. 7 CIRCUIT USED FOR EXPERIMENTAL MEASUREMENTS

The optimum value of the collector load resistor was 1000 ohms. Considerable care was taken to shield the low level signal lead coming from the collector to the input of the video amplifier.

Fig. 8 is a plot of detected output signal level versus collector voltage for constant input. Beam voltage was the same as for the curves in Plates I and II. Beam current was optimized for maximum output. As can be seen, the detected output peaked at a value of about 4 volts, as would be expected.

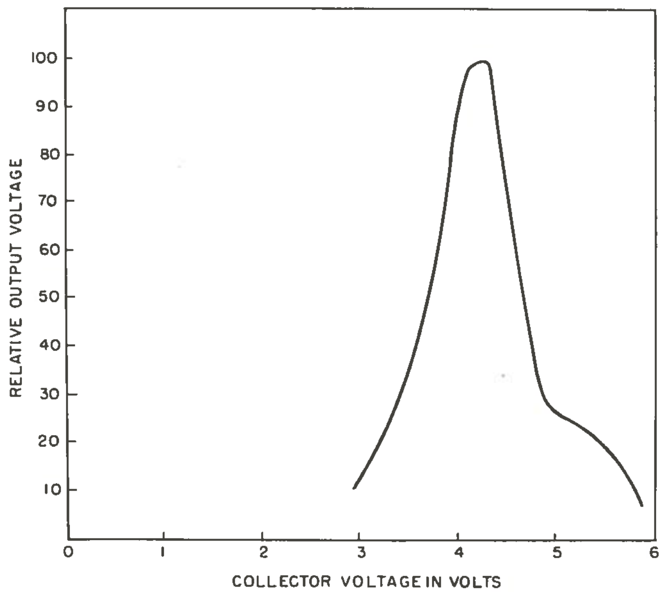

FIG. 8 DETECTED OUTPUT LEVEL VERSUS COLLECTOR VOLTAGE

An important characteristic of the autodyne detector is the rate at which output signal is reduced as beam current is increased beyond starting current. In Fig. 9 normalized output from the two types of detector is plotted against normalized beam current. One hundred on the abscissa represents starting current. It is apparent that the crystal detector is much less sensitive to beam current. Note that in contrast to the case with crystal detector operation, collector detection efficiency falls off almost as rapidly above starting current as it does below.

With crystal detection, the detected output falls off rapidly below starting current because the gain decreases rapidly. Above starting current, the gain decreases because the beam bunching becomes non-linear at large oscillator outputs, and the modulation on the electron beam due to the signal is suppressed.

In the case of detection on the collector, an additional factor is introduced. The actual efficiency of detection after the beam has left the delay line region, depends very strongly on beam current. This can be explained in the following way. The change in collector current, which represents the video output, is brought about by a change in the velocity distribution of the electron beam. If the signal and the oscillation are equal in amplitude, the resulting beam velocity distribution will vary from a thermal distribution, to one due to the sum of the signal plus oscillation. The latter variation will take place at the difference frequency. Suppose that the signal is very small, of the order of -90 dbm. It was pointed out earlier, on the basis of the simplified model, that collector current was a non-linear function of modulation on the beam. At beam currents only very slightly above oscillation starting point, oscillation power output will be 100 times as great as the signal (-70 dbm). At this point, collector current is relatively insensitive to small percentage changes in velocity. This means that the efficiency of collector detection decreases rapidly when either the signal or the oscillation is large with respect to the other.

This is further illustrated by measurement of the dynamic range of the detector. The output versus input is plotted in Fig. 10 for constant beam current. By increasing beam current with increasing signal, the output could be maintained constant, as shown.

CONCLUSIONS

A study was made of the application of a retarding-field velocity-sorting detector to microwave autodyne receivers. The study showed that:

1) the presence of a radio-frequency signal at the input to the delay line of a backward-wave autodyne receiver can be detected by a negatively biased collector;

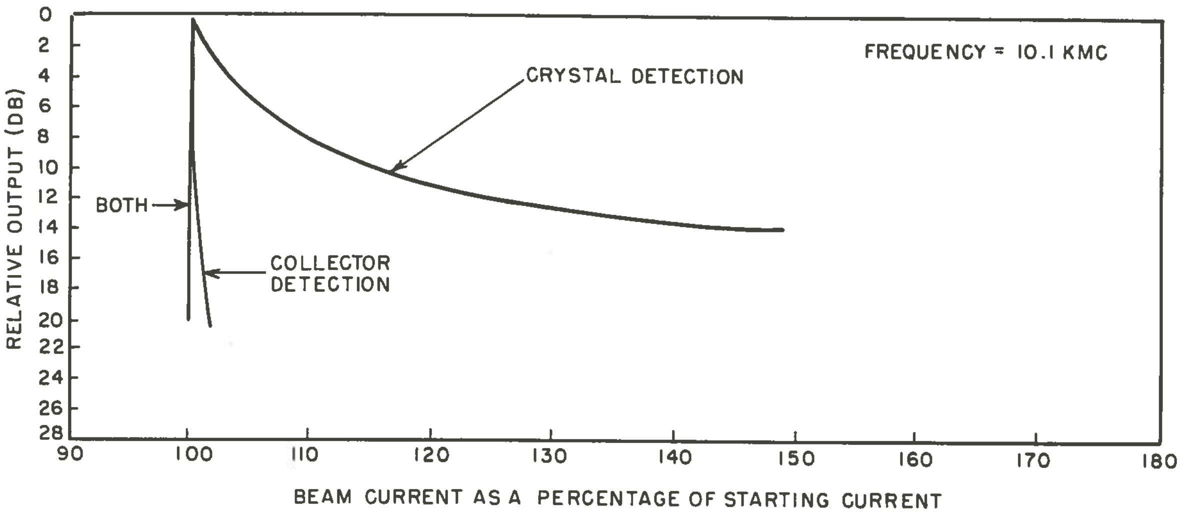

FIG. 9 NORMALIZED OUTPUT VERSUS BEAM CURRENT FOR TWO TYPES OF DETECTOR

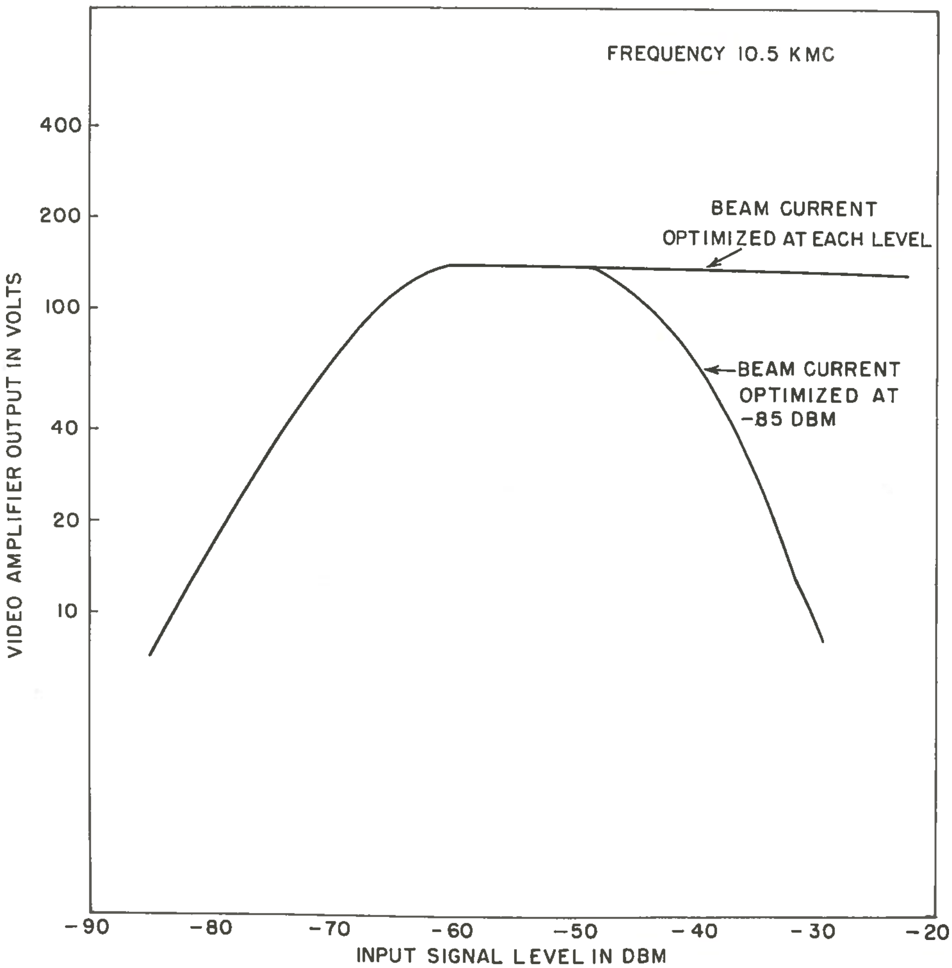

FIG. 10 DYNAMIC RANGE OF COLLECTOR DETECTOR

2) the over-all sensitivity of the receiver is high, and is limited only by the noise figure of the backward-wave tube;
3) the video output versus radio-frequency input characteristic is non-linear, and the maximum usable dynamic range is approximately 20 db;
4) the efficiency of detection decreases very rapidly as the beam current is raised above starting current, so that extremely rigid beam current control is required, and the tube is therefore not suited for use in an electronically tuned receiver;
5) the formation of a virtual cathode at the collector was not satisfactory for velocity-sorting detection with the tubes used in this investigation;
6) other types of velocity-sorting detectors which would give an output proportional to velocity spread rather than to the number of electrons below a given velocity, would not be as sensitive to beam current and would, therefore, be more satisfactory.

ACKNOWLEDGMENT

The author is indebted to W.L. Haney who suggested the collector detection scheme, and to other members of the staff of the Radio and Electrical Engineering Division for helpful discussions during preparation of the report. Measurements were made by H. Poapst.

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PLATE I THREE-DIMENSIONAL GRAPH OF MEASURED COLLECTOR CURRENT FOR TYPE VAD-161-4 TUBE

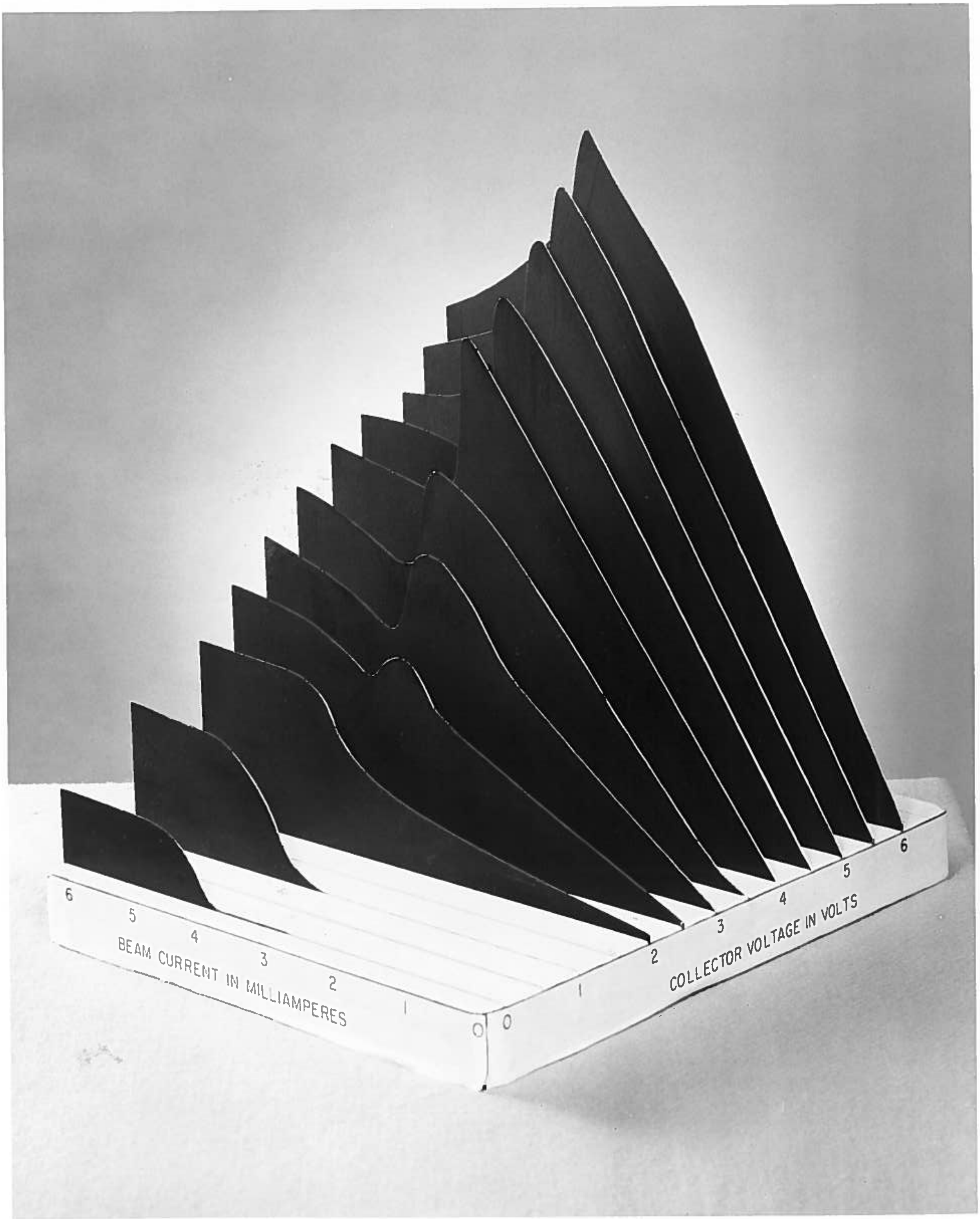

PLATE II THREE-DIMENSIONAL GRAPH OF MEASURED COLLECTOR CURRENT FOR TYPE VAD-161-4 TUBE