FREQUENCY STABILIZATION OF A KLYSTRON IN A PARAMAGNETIC RESONANCE SPECTROMETER

by

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ABSTRACT

A field modulation, paramagnetic resonance spectrometer in use as a wide band instrument employs a reflex klystron. The frequency of the klystron has been stabilized to at least one part in one quarter million, over a period of a few hours, to the resonant frequency of a microwave cavity. A variation of the R.C. Pound stabilizing circuit was employed.

With field stabilization, this frequency stabilization makes it possible to operate the spectrometer as a narrow band instrument, thereby increasing the overall sensitivity.

ACKNOWLEDGMENTS

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INTRODUCTION

In an experimental study of paramagnetic resonance, the two quantities measured are the frequency of the exciting radiation and the magnetic field. To obtain reproducible experimental results of a given accuracy, both of these quantities should be stabilized.

A spectrometer can be operated in a wide or a narrow band manner. In wide band operation where measurements are made in a few minutes, only short term frequency and field stability is necessary, whereas in narrow band operation, long term stability is required as measurements are made in a few hours. The high sensitivity, double modulation, wide band spectrometer in this laboratory possess the required short term stability. If long term frequency and field stability could be achieved, then narrow band operation can be executed, resulting in an increase in sensitivity of the spectrometer by a factor of about 100.

This thesis deals with the stabilization of the frequency, the field stabilization being left as a separate problem.

CHAPTER I.

FREQUENCY STABILIZATION IN A PARAMAGNETIC SPECTROMETER

Introduction

In this chapter an indication of the phenomena of paramagnetic resonance is noted. The two major types of operation of a spectrometer are described, the narrow and wide band. The two wide band spectrometers, in operation in this laboratory, are then described. It is then shown that in both these spectrometers, it is important to stabilize the frequency of the microwaves generated by a reflex klystron.

1.1 Paramagnetic Resonance

The phenomena known as magnetic resonance results when a particle with a magnetic moment is placed in a steady magnetic field. The magnetic moment of the particle precesses about the direction of the steady magnetic field such that the particle has the lowest energy possible. If a periodic magnetic field is applied at right angles to the steady magnetic field and if the frequency of the periodic field is equal to the frequency of the precessing magnetic moment, then the particle's magnetic moment flips over such that the particle has a higher energy; this energy being absorbed from the fluctuating field. This action, we can call a transition. Many such transitions combine to produce a resonance which is observed by the energy absorbed from the periodic magnetic field.

Paramagnetic resonance arises by the above method from paramagnetic ions which have a partly filled electron shell. Such ions have a resultant angular momentum due partly to orbital motion and partly to the intrinsic spin of the electrons. The resultant angular momentum gives rise to a permanent magnetic moment which will have the same direction as the angular momentum. It has been found that the quantum mechanical explanation of this phenomena is quite successful. In a simple case, where only two energy levels of the paramagnetic ion exist, the energy absorbed in the transitions occur in quanta equal to $h\nu = g\beta H$, ν = frequency of the periodic field; g = spectroscopic splitting factor;, β = the Bohr magneton. This relationship known as Kramers doublet relation makes it possible to observe resonances as a function of ν or H, the other being kept constant. When paramagnetic resonance experiments are performed at microwave frequencies, it is found necessary to hold ν fixed and vary H because of the type of oscillator used. These experiments are usually carried out at a wavelength of a few centimeters, the magnetic field being a few kilogauss; i.e. for $g = 2$, $\nu = 25$ kilomega cycles per second, H is about 8,800 gauss. It is desirable to use short wavelengths since the sensitivity is inversely proportional to the wavelength. The use of wavelengths shorter than one centimeter has been restricted by the lack of suitable sources and detectors of radiation in this region.

1.2 Wide and Narrow Band Spectrometer Operation

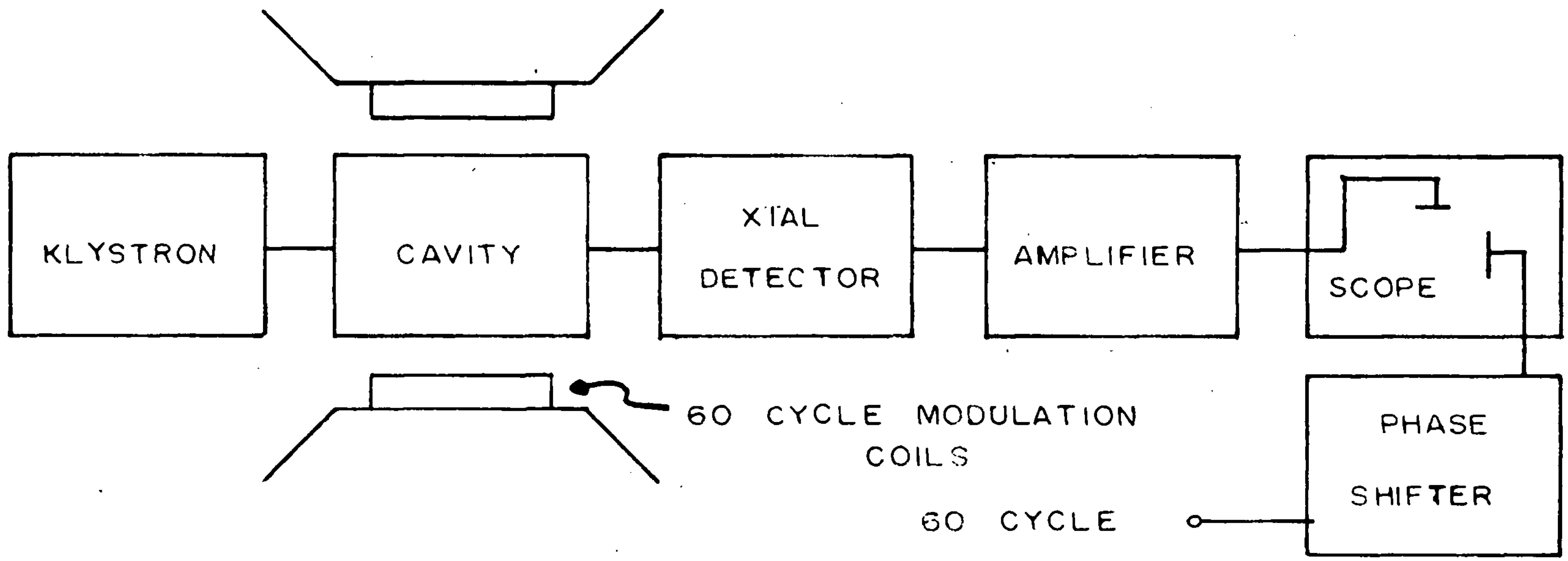
The spectrometers employed to observe the phenomena of paramagnetic resonance at short wavelengths employ distributed parameter circuitry. The sample under observation is placed in a tuned cavity instead of an extended waveguide for two reasons

(a) The sample must be located in a strong homogeneous magnetic field

(b) The samples are usually small single crystals and the highest sensitivity is obtained by concentrating the microwave magnetic field on them.

There are two types of operation of paramagnetic spectrometers, (a) the wide band, (b) the narrow band. In wide band operation, the steady magnetic field is modulated at a low frequency with an amplitude greater than an absorption line width at half power expressed in terms of the magnetic field. When centered on a resonance line, the magnetic field swings through the region of the resonance, thereby making it feasible to observe the resonance curve on some recording device. The energy absorbed during a paramagnetic resonance, amplitude modulates the microwave power level at the field modulation frequency. This modulation is detected, amplified by a broad band amplifier to preserve line shape, and displayed on an oscilliscope. (ref. 1).

In narrow band operation, the steady magnetic field is modulated at a low frequency, the modulation having an amplitude



SINGLE MODULATION SPECTROMETER

FIG. 1

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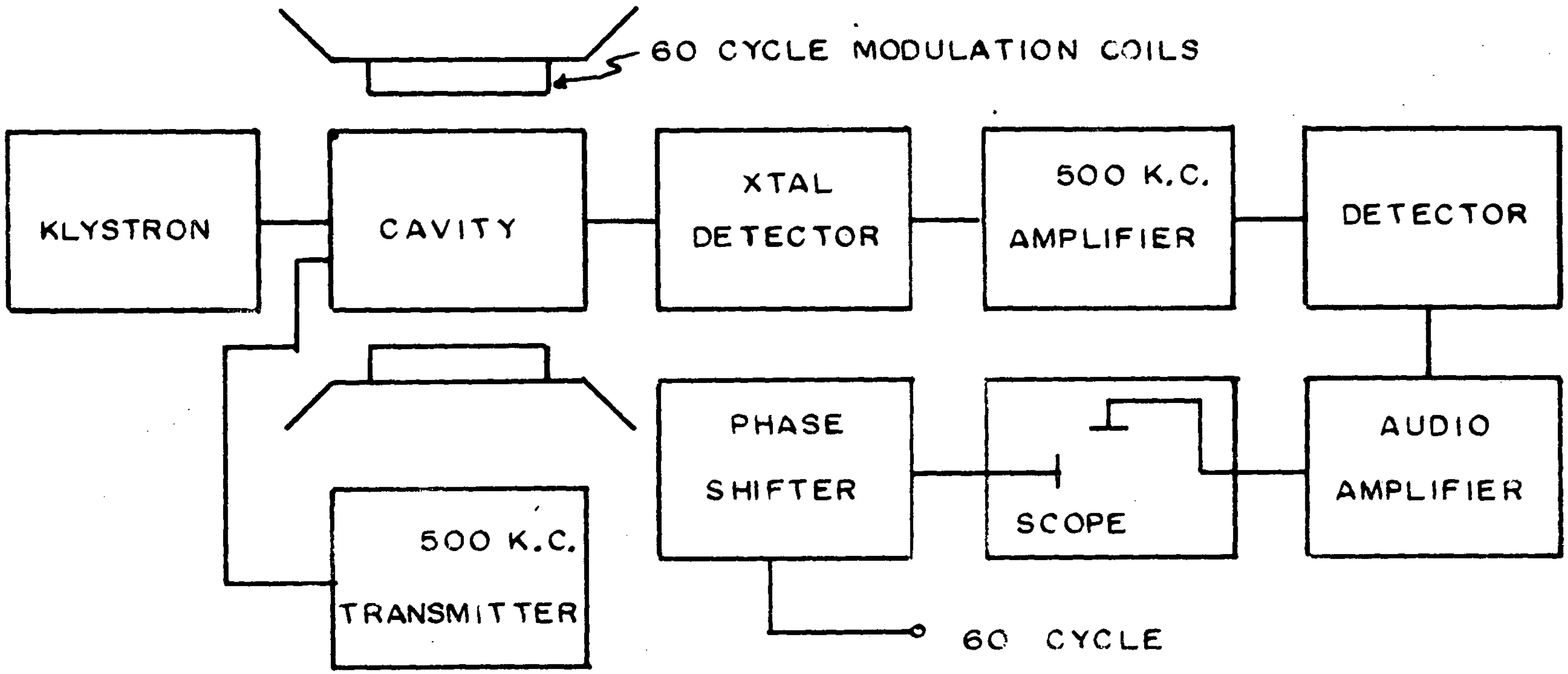

DOUBLE MODULATION SPECTROMETER

FIG. 2

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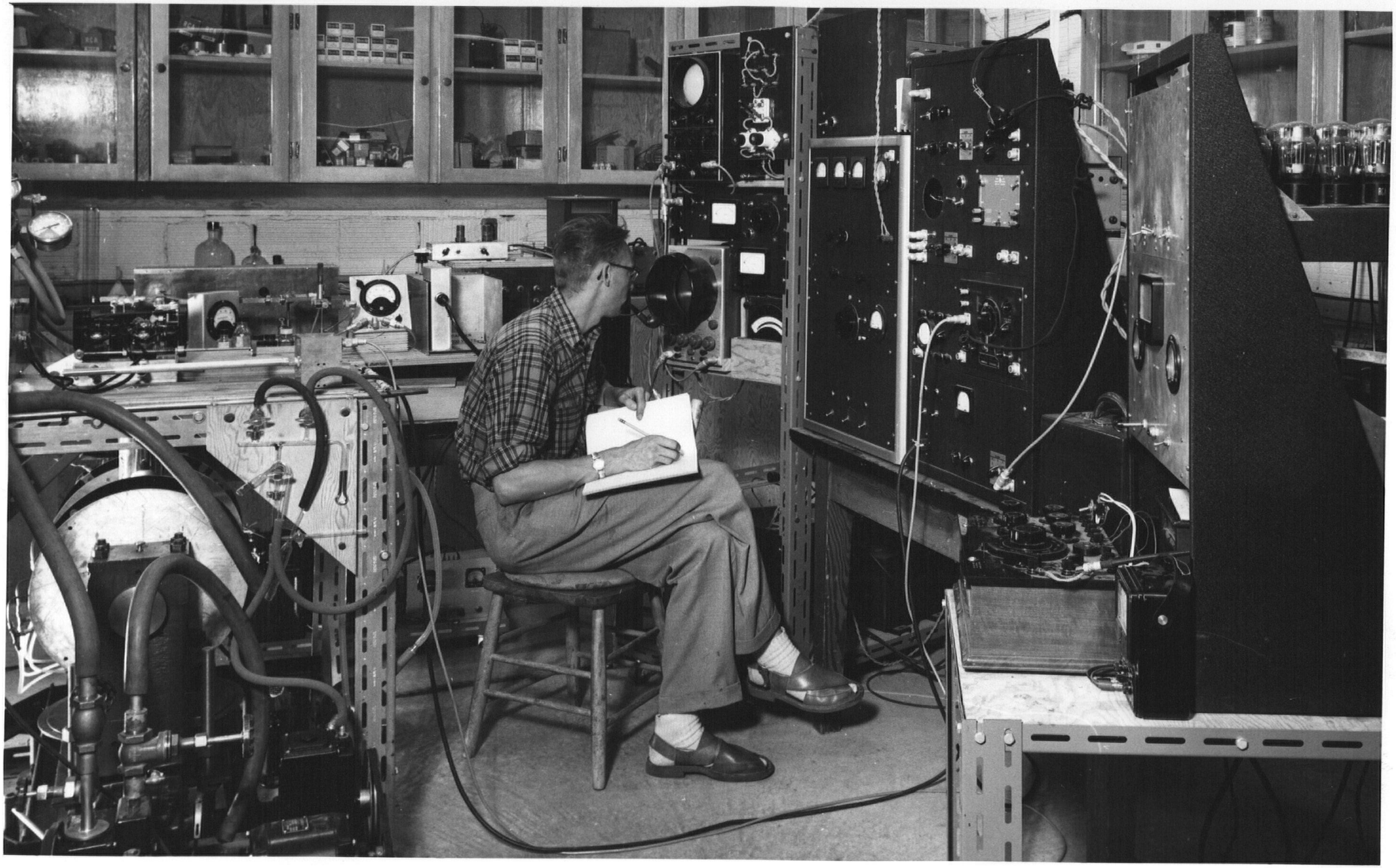
less than the line width. As in wide band operation, we obtain an amplitude modulation on the microwave power level which is detected, amplified in a narrow band amplifier, converted to D.C. and displayed on a pen recorder. This procedure gives one point on the absorption curve. To obtain the entire curve, the steady magnetic field is slowly changed. The recorder then reproduces the first derivative of the absorption line. Since the noise generated by an amplifier is proportional to the band width, the narrow band operation greatly reduces the noise of the spectrometer, provided the noise generated by the detector is not overwhelmingly large. Because the noise is greatly reduced, the deciding factor for sensitivity of the spectrometer is the stability, rather than the noise as in wide band operation. Thus frequency stabilization is an important problem for narrow band operation.

1.3 Wide Band Spectrometers Employed in the Laboratory

In this laboratory there are two wide band, field modulation spectrometers employing a frequency of 24 kilo-megacycles per second i.e. a wave length of 1.25 centimeters. In both systems, a reflex klystron generates the microwave radiation which is transmitted by wave guides to a transmission cavity (as compared to a reflection type cavity). The difference between the two spectrometers is in the field modulation, one using a single modulation and the other a double modulation. The single modulation spectrometer (fig. 1),

Plate I



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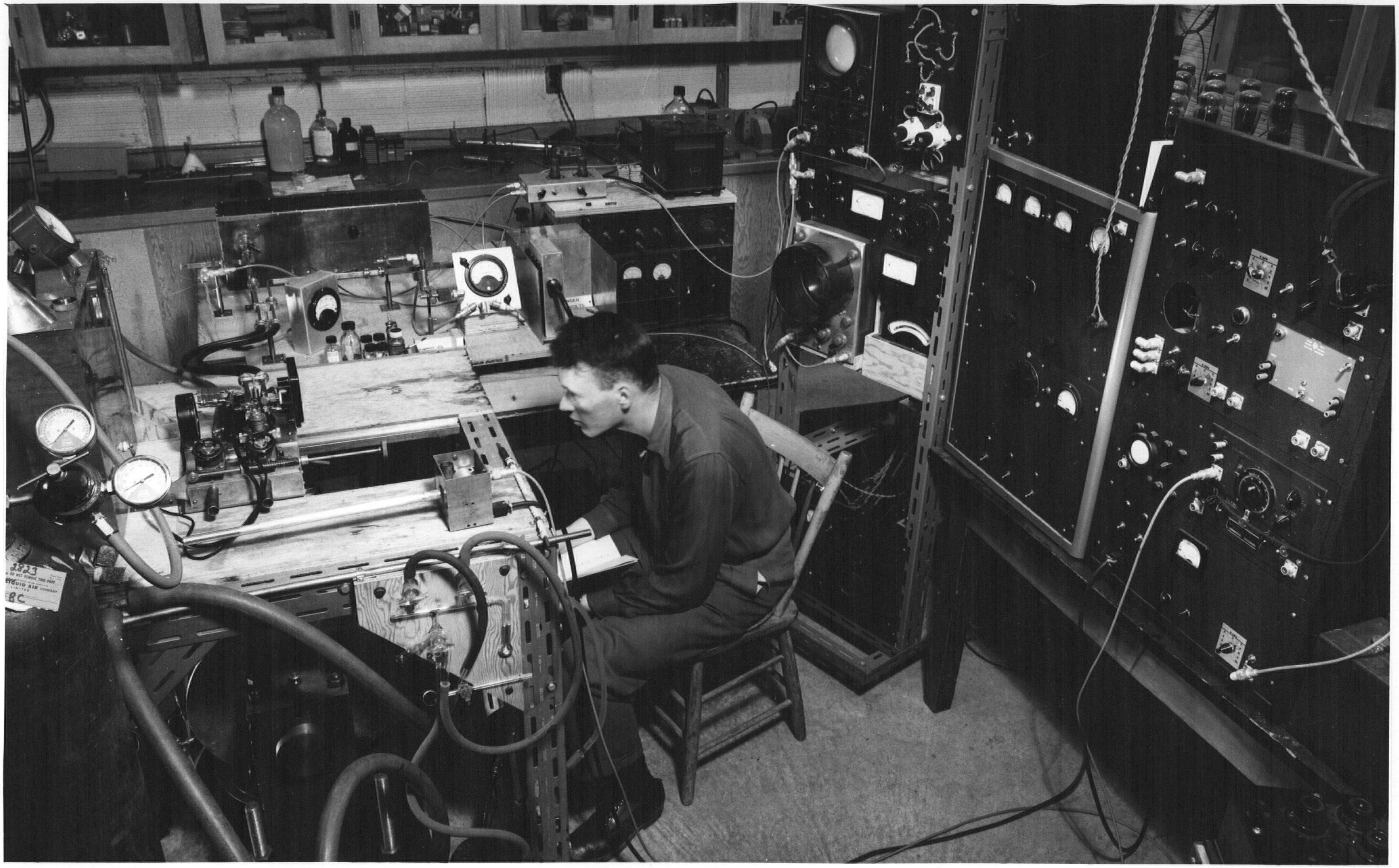
General View of the Spectrometer

Plate II



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General view of the Spectrometer

employs a 60 cycle modulation. The resulting modulated microwaves are detected in a crystal converter. The resonance signal is then displayed on an oscilliscope after amplification.

The second spectrometer (fig. 2) employs a double modulation of the magnetic field. In addition to the 60 cycle sweep covering at least the line width, a 500 kilocycle per second sweep covering at most the line width is also used. The 500 kilocycle component of the modulation is detected, amplified in a broad band amplifier. The 60 cycle component is then detected, amplified and displayed on an oscilloscope. The first derivative or its modulus is obtained. It may be mentioned that a high sensitivity has been obtained with this spectrometer since the crystal detector detects a high frequency (ref.2). A picture of the combined spectrometer is shown in Plates I and II.

1.4 Fixed Frequency Considerations

Both spectrometers operate at fixed frequency, resonances being observed as a function of the magnetic field. As stated before (1.1), the main reason is due to the nature of the microwave generator or reflex klystron. A reflex klystron oscillates in different modes, a mode being several hundred megacycles per second wide. Further, it is very difficult to vary the frequency over a large range. The output power depends drastically on the mode of operation.

In practice the condition of a constant frequency is difficult to obtain. The factors affecting short term stability (over a period of a few minutes) are the following:

(a) Short term fluctuations in the reflex klystron power supply will cause short term frequency shifts in the klystron output.

(b) The output frequency of the reflex klystron is a function of the impedance it works into. This impedance is partially determined by the standing wave ratio of the microwave system. This ratio depends on the reflection coefficient of the cavity which in turn is a function of the energy absorbed in it. This change in reflected energy, will result in a pulling of the klystron's frequency. The main factors affecting long term stability (over a period of a few hours) are the following:

(a) Long term fluctuations in the reflex klystron power supply will cause long term frequency shifts in the klystron output.

(b) Within the reflex klystron there is a resonator giving rise to resonances by electrons passing through it. This is the basis for the generation of microwaves. The frequency of the microwaves will be affected by the resonant frequency of this resonator. As the klystron continues operation, it becomes warm, thereby, expanding the resonator in the klystron and changing the frequency of its output. This is known as thermal drift of the klystron.

(c) The pulling effect of the klystron will also contribute to the long term stability.

1.5 Amplitude Considerations

In both spectrometers, the amplitude of the resonance observed is proportional to the microwave energy in the cavity, since it is the field of the microwaves which induce the transition. The microwave power level in the cavity is determined by three factors.

(a) The operating conditions of the klystron must be carefully selected because the microwave power depends upon the mode of operation and the position within the mode.

(b) The magnitude of the Q of the cavity indicates how much of the microwave energy is absorbed and how much can be considered useful energy. Most cavities have a Q of about 10,000.

(c) To take advantage of the high Q of the cavity, the frequency of the microwaves should be at the resonant frequency of the cavity. Since $Q = \frac{\nu}{\delta\nu}$ where $\delta\nu$ is the width of the cavity resonance curve at the half power points, then for a Q of 10,000 and a frequency of 25 kilomegacycles per second, $\delta\nu$ is 2.5 megacycles. This shows that if the frequency is stabilized to only one part in 10^4 there can be a fluctuation of 50% in the microwave energy in the cavity. However, if the frequency is stabilized to one part in say, 10^6 and is at the cavity's resonant frequency, then the energy of the microwaves in the cavity will remain essentially at the maximum value.

Because of the necessity for a constant frequency during a set of meaaurements and of the desirability of a maximum amplitude of the resonance signal it is important to stabilize the frequency of the klystron to the resonant frequency of the cavity to approximately one part in 10^6 for the time of recording a measurement.

CHAPTER II.

METHODS OF STABILIZATION

In this chapter, the various methods employed for stabilizing a reflex klystron will be described and discussed from the standpoint of feasibility to the present problem of stabilizing the frequency of the klystron to the resonant frequency of the cavity. The chosen method must not interfere with the observation of paramagnetic resonance.

2.1 Resonant frequency considerations

It may be noticed that we are not interested in stabilizing the frequency to a fixed value but only to the resonant frequency of the cavity. While the frequency stability is limited by the stability of the resonant frequency, the amplitude of the microwaves in the cavity, and thus the intensity of the paramagnetic resonance, is held reasonably constant. Any changes which are present in the microwave intensity will arise from the shape of the power vs. frequency curve of the mode of operation of the klystron.

The resonant frequency of the cavity is subject to short term instabilities and long term instabilities. The short term instabilities are caused by short term temperature fluctuations and mechanical vibrations of the cavity. The long term instabilities will be caused by long term temperature fluctuations and variations of the contact of the running plunger threads with the cavity. The short term instabilities in the resonant frequency are not serious for the high sensitivity, double field modulation spectrometer with wide band operation. However, with narrow band operation it is probable that the long term instabilities would limit the sensitivity. These long term instabilities can be minimized by immersing the cavity in a liquid which is preferably at its boiling temperature.

Such changes in the resonant frequency caused by the presence of dielectric materials, as helium, in the cavity or by a large change in temperature, as from room temperature to liquid helium temperatures, can be corrected for by mechanical tuning of the klystron or detuning the klystron in the correct direction before the occurrence of the change in the resonant frequency.

2.2 Existing Methods

As the klystron power supply is electronically regulated, the short and long term instabilities due to this cause are kept to a minimum. The short term instabilities present in the high sensitive, double field modulation spectrometer are mostly due to the pulling effect of the cavity. The long term instabilities present, result mostly by the thermal drift and the pulling effect. Along with these effects, the instabilities in the resonant frequency of the cavity, described in 2.1, are present. The chosen method must lock the frequency of the klystron output to the resonant frequency of the cavity, regardless of the instabilities present.

The thermal drift of the klystron and temperature effects of the cavity can be minimized by allowing the spectrometer to warm up to an equilibrum temperature. Further, the klystron could be immersed in an oil bath to minimize thermal effects due to temperature fluctuations in the laboratory. However, only an electronic method can deal with the thermal, pulling, and mechanical effects simultaneously. Hence it was decided to use such a method.

The various existing electronic methods have been designed to stabilize a reflex klystron's frequency to a fixed frequency, the fixed frequency usually being the resonant frequency of a cavity. These methods of frequency control shall first be presented as they exist for this function, before discussing their applicability to the present problem.

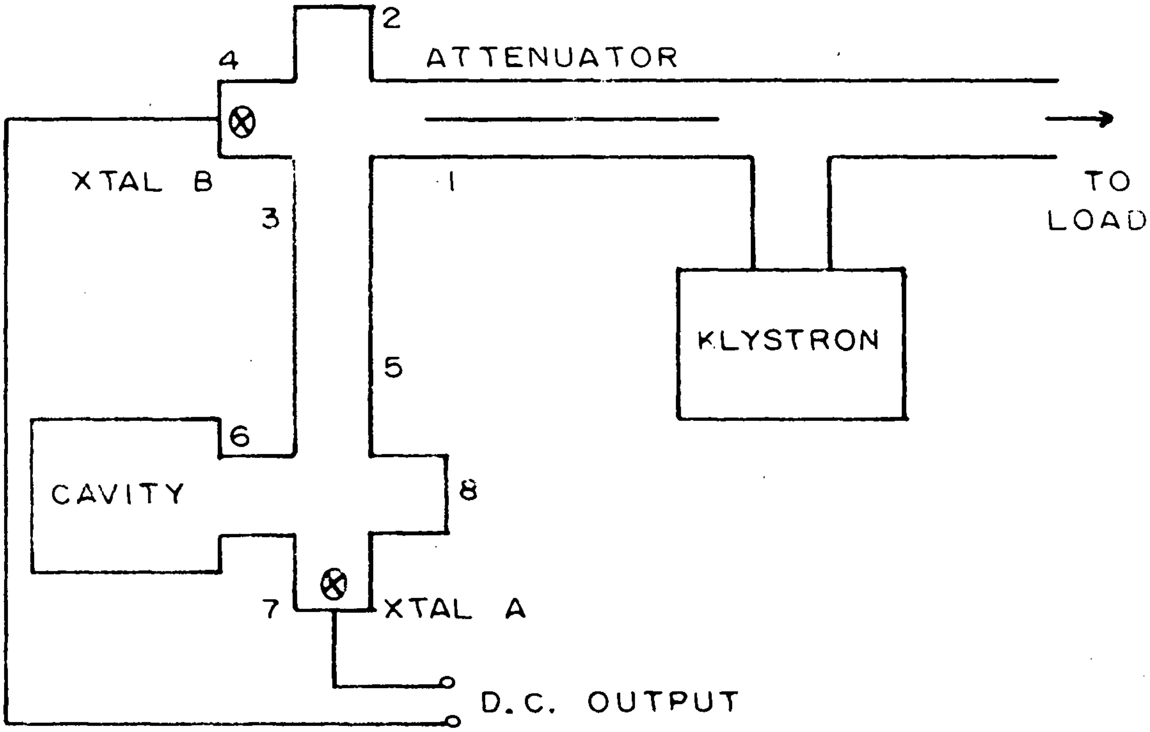
There exist three catagories of methods.

a. D.C. method

b. Molecular or atomic absorption method

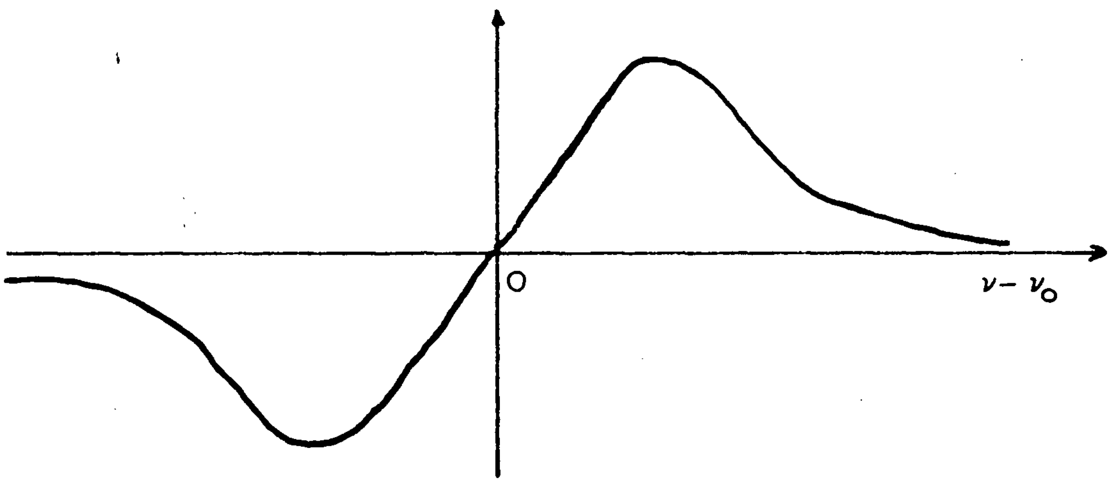
c. The A.C. method.

The first and last methods have several variations which will be described. These three methods have the following common property. As the frequency of a klystron is a linear function of its reflector voltage over a small range of operation in any particular mode, a D.C. correction voltage proportional to the frequency error is created and applied to the klystron's reflector. To obtain this correction voltage, use is made of a frequency discriminator containing a cavity in the microwave



MICRO-WAVE DISCRIMINATOR

FIG. 3 A



D.C. OUTPUT

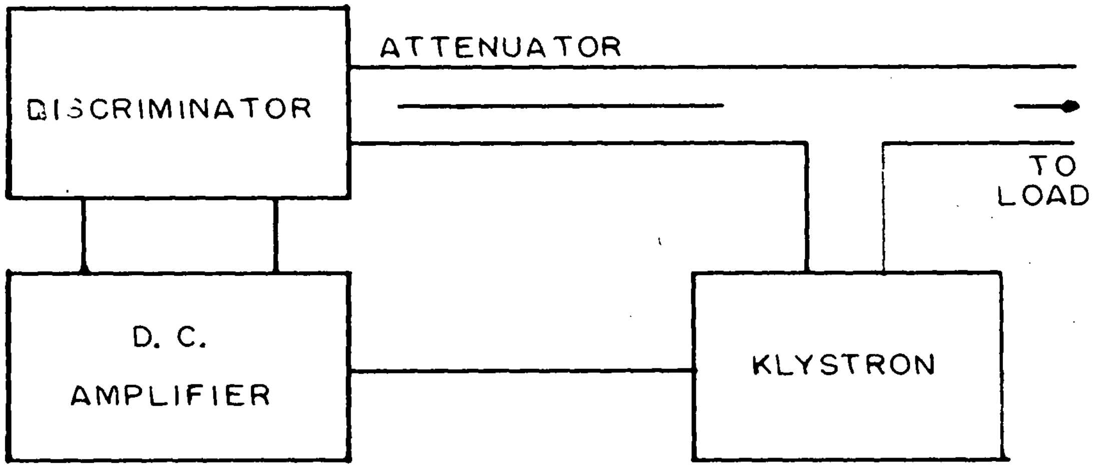
FIG. 3 B

To be facing page 13

circuit, as is done in the D.C. method, or use is made of an auxiliary oscillator whose signal acts as an information collector on the difference between the frequency of the klystron and a reference, such as, a microwave cavity's resonant frequency as is done in the A.C. and absorption methods.

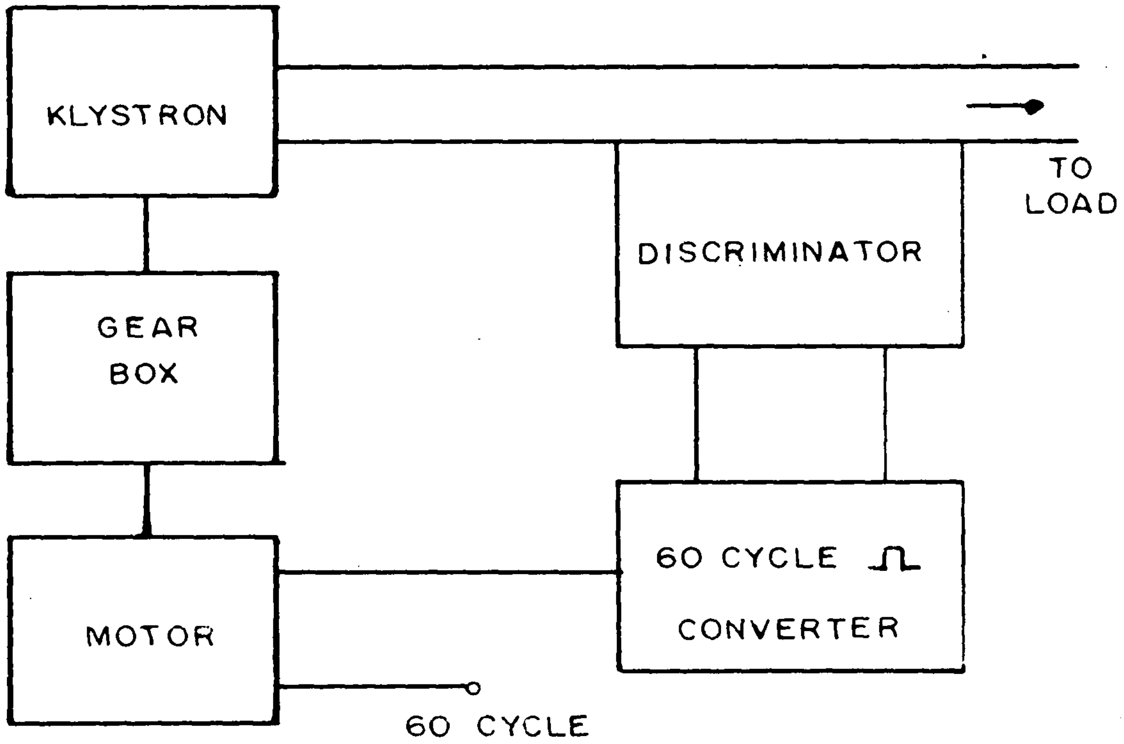
2.3. D.C.Methods

There are two main variations of this method one developed by R.V. Pound (ref. 3,4,5,6) and the other developed by V.C. Rideout (ref. 7). The microwave discriminators employed by these two people are similar, both employing two magic tees. The discriminator due to R.V. Pound shall now be described (fig. 3). Two magic tees are joined, as shown in figure 3A. An attenuator separates the klystron and discriminator. Two crystal detectors are present in arms 4 and 7 and a cavity is joined to arm 6. The D.C. output of this discriminator is shown in figure 3B as a function of $\nu - \nu_0$, ν being the frequency of the klystron, ν_0 the resonant frequency of the cavity. The operation can be explained qualitatively by the following arguements. The klystron's output is divided between the load and regulating circuit, the attenuator causing the majority of the microwave energy to go to the load. The attenuator also serves as a matching device of the load to the klystron. The energy which enters the regulator circuit after passing through the attenuator is divided equally between arms 2 and 3. Arm 2 is terminated so that there is no reflection from it. That in arm 3, enters arm 5 and is divided equally



POUND'S D. C. CIRCUIT

FIG. 4



RIDEOUT'S D.C. CIRCUIT

FIG. 5

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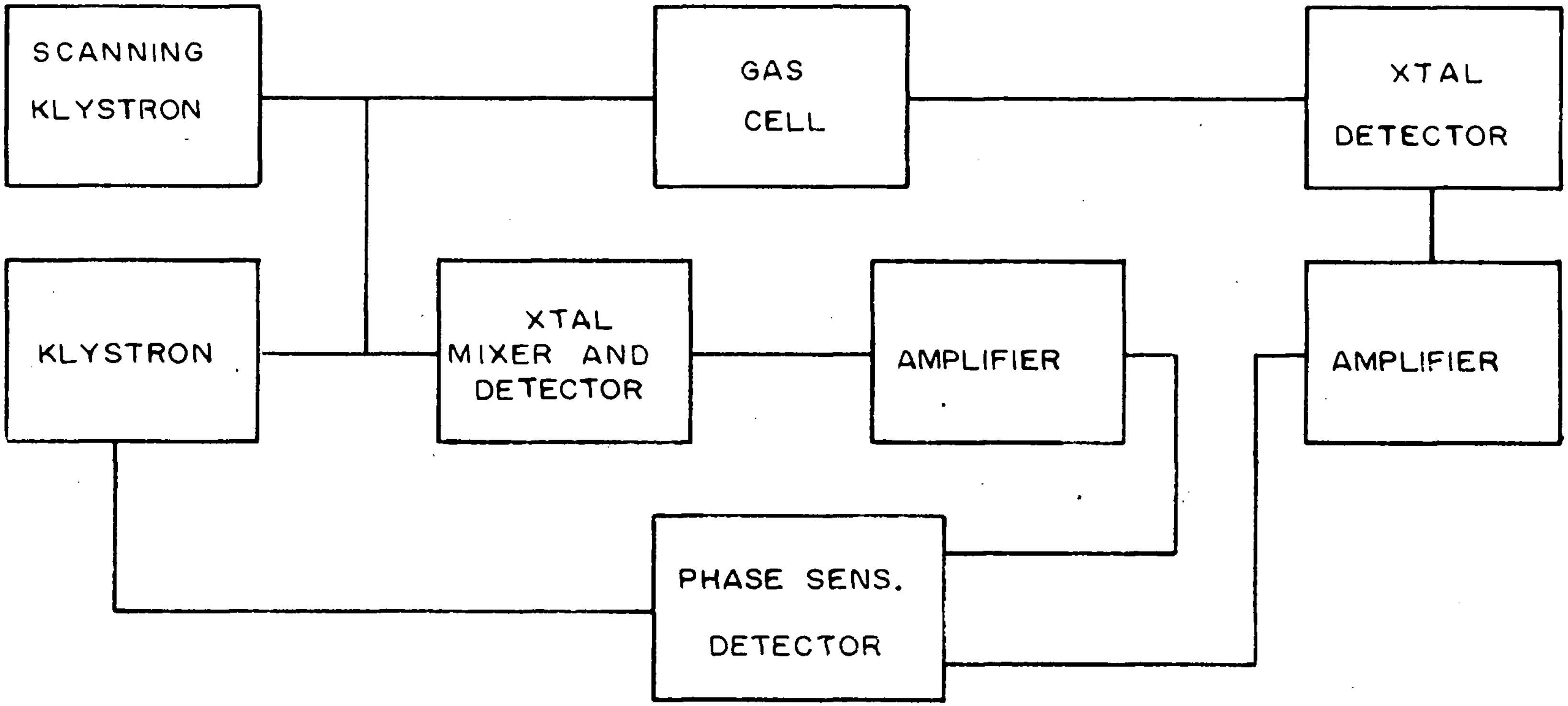
between arm 8 which is terminated to prevent reflection and arm 6 which leads to the cavity. The cavity reflects when $\nu \neq \nu_0$ and doesn't reflect if $\nu = \nu_0$. The result of this action is that when $\nu \neq \nu_0$, there is more energy in arm 6 than in arm 8 thus some energy arrives at crystal A in arm 7. A small amount of the reflected energy will also find its way to crystal B in arm 4. The sign of the D.C. output depends whether $\nu < \nu_0$ or $\nu > \nu_0$. In each of these two cases, the phase of the reflected microwaves is 180° different from the other case, resulting in a cancellation or addition in arm 6 which causes the D.C. output to be negative or positive.

The Pound circuit (fig.4) amplifies this D.C. correction voltage and applies it to the klystron's reflector. The Rideout circuit (fig. 5) converts this D.C. correction voltage to 60 cycles A.C. which is amplified and applied to the control phase of 2-phase, low inertia, induction motor. A reference 60 cycle signal is applied to the other phase. This motor turns a mechanical tuning shaft on the klystron via a reduction gear box. If the correction voltage is zero, then the motor doesn't turn, if there is a D.C. correction voltage, then 60 cycles A.C. is obtained, the phase depending on whether the D.C. correction voltage is negative or positive. The motor then turns in the direction determined by the phase of the 60 cycle A.C. This is actually a servo-mechanism and removes only slow variations in the frequency of the klystron.



MOLECULAR ABSORPTION METHOD

FIG. 6

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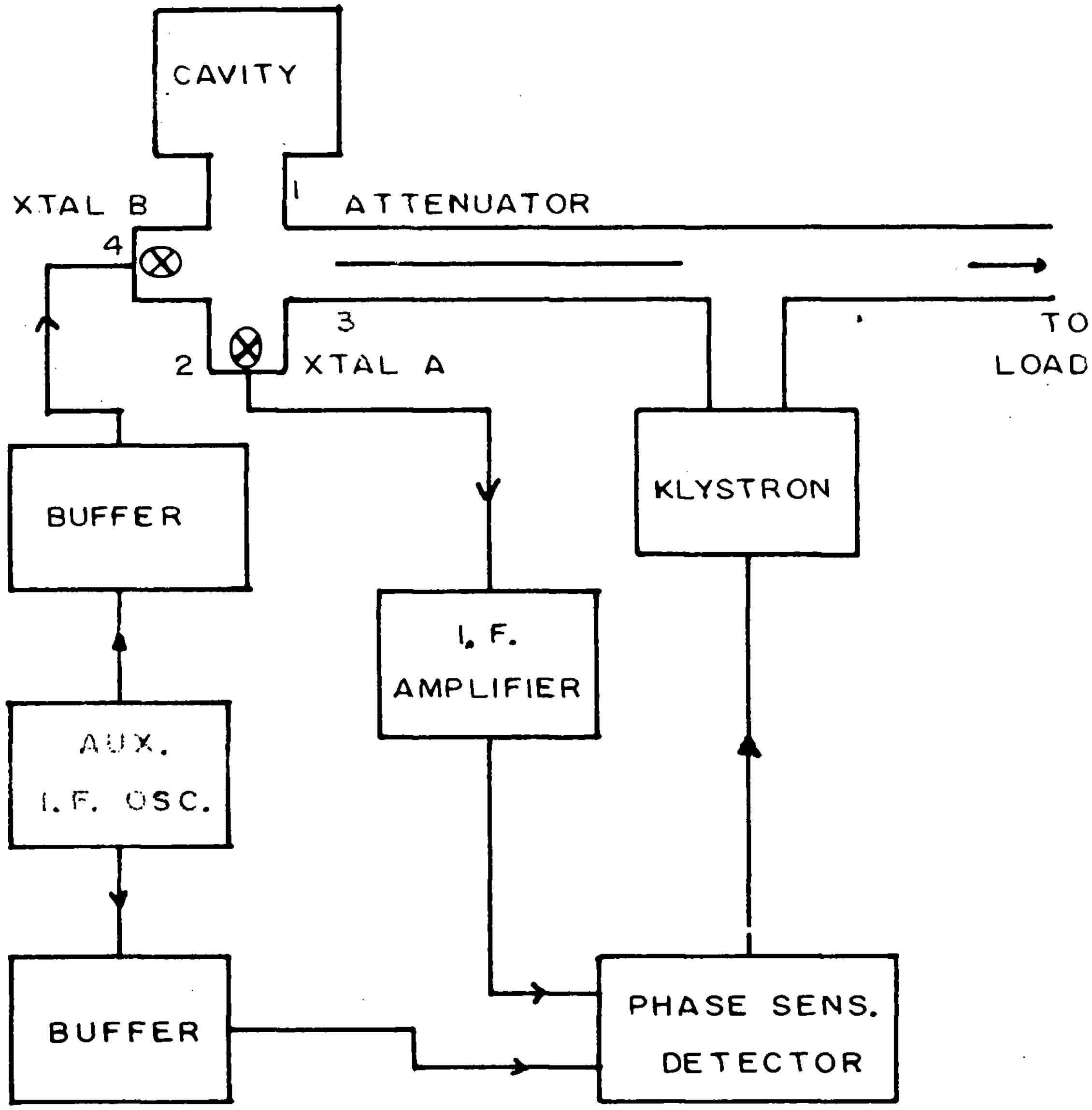
2.4 Absorption Method

This method uses an atomic or molecular absorption line as a reference frequency source. Essentially, the frequency of the klystron is compared with the frequency of the absorption line. A D.C. correction signal proportional to the difference of the two frequencies is developed and applied to the reflector of the klystron. The development of this method is due to W.D. Hershberger, L.E. Norton, H.R.L. Lamont and others (ref. 8,9, 10,11) who have mainly used the inversion spectrum of ammonia.

One circuit used is shown in fig. 6 (ref.8). In this circuit a scanning klystron is frequency modulated at some intermediate frequency. The sweep in its frequency covers the absorption line and the stabilized klystron's frequencies. A periodic absorption occurs in the gas cell at a frequency of the modulation on the scanning klystron. This signal is then detected, amplified, and made to enter a phase sensitive detector, where it is compared with the difference in frequency of the two klystrons. A D.C. voltage is developed in the output (see appendix A). This D.C. voltage is applied to the reflector of the stabilized klystron and locks its frequency. The line width of the gaseous absorption is the determining factor for accuracy. It can be noticed that this is an excellent method for stabilizing an oscillator to one fixed frequency, but not to the varying resonant frequency of a cavity.



POUND'S A. C. CIRCUIT

FIG. 7

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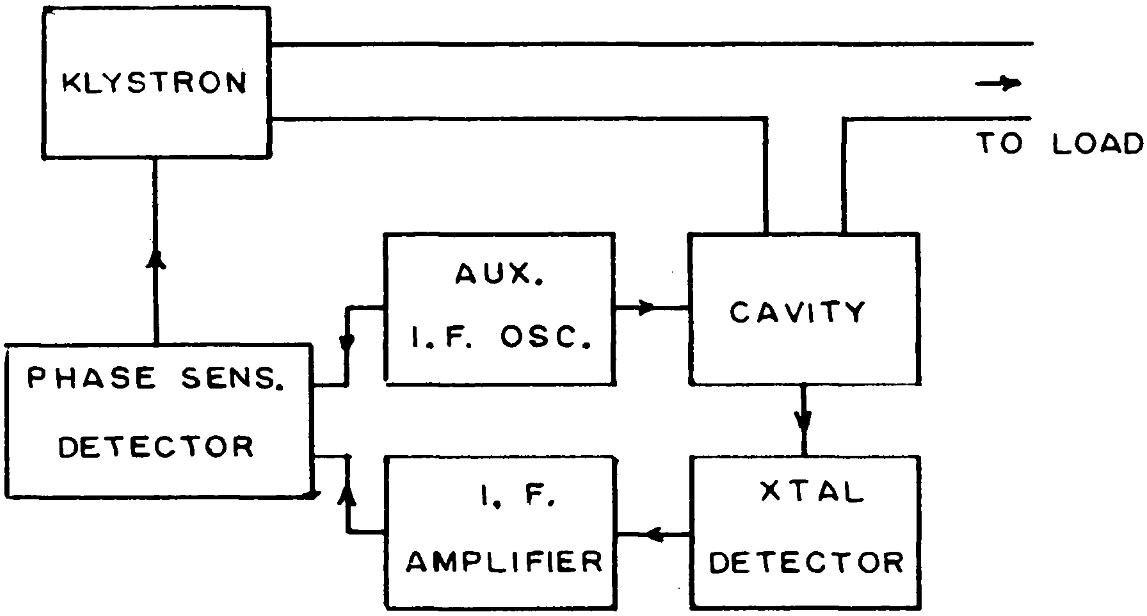
2.5 A.C. Method

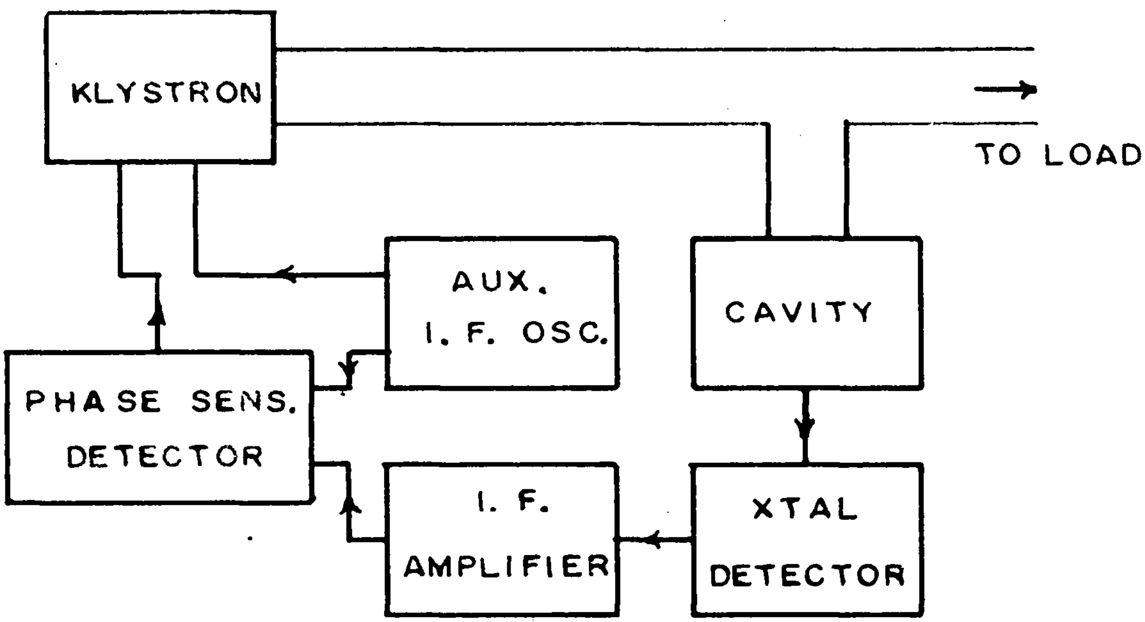
There are three variations of this method. The first variation is due to R.V. Pound (ref. 3,5), the other two are mentioned by E.F. Grant (ref. 12).

The Pound circuit shown in fig. 7, employs a magic tee. A cavity of resonant frequency ν_0 is on arm 1; two mixer crystals are on arm 2 and 4. The operation of this circuit can be explained qualitatively by the following arguments. As in the Pound D.C. method, the klystron output is divided between the load and the stabilizing circuit, the attenuator causing the majority of the energy to reach the load. The energy present in arm 3 divides equally between arms 1 and 2. The energy in arm 1 is not reflected by the cavity if $\nu = \nu_0$, but is reflected if $\nu \neq \nu_0$. if the energy is reflected, it divides evenly between arms 4 and 3. That part in arm 3 is lost to the attenuator and that part in arm 4 is mixed at crystal B with a signal from the I.F. auxiliary oscillator. Hence there are two side bands $\nu_k \pm \nu_a$; ν_k = the frequency of the klystron, ν_a = the I.F. frequency of the auxiliary oscillator. These bands are reflected and evenly divided between arms 1 and 2. Those entering arm 1 can be neglected as they give rise to only second order effects. Those entering arm 2 mix at crystal A with the original ν_k. We then have at crystal A, three frequencies -- ν_k and $\nu_k \pm \nu_a$. The output used from crystal A is at the I.F. frequency which has a voltage of $E = \frac{\sqrt{2}}{4} E_0 |\Gamma_0| m \cos\delta \cos(2\pi \nu_a t)$.



CAVITY MODULATION METHOD

FIG. 8



FREQUENCY MODULATION METHOD

FIG. 9

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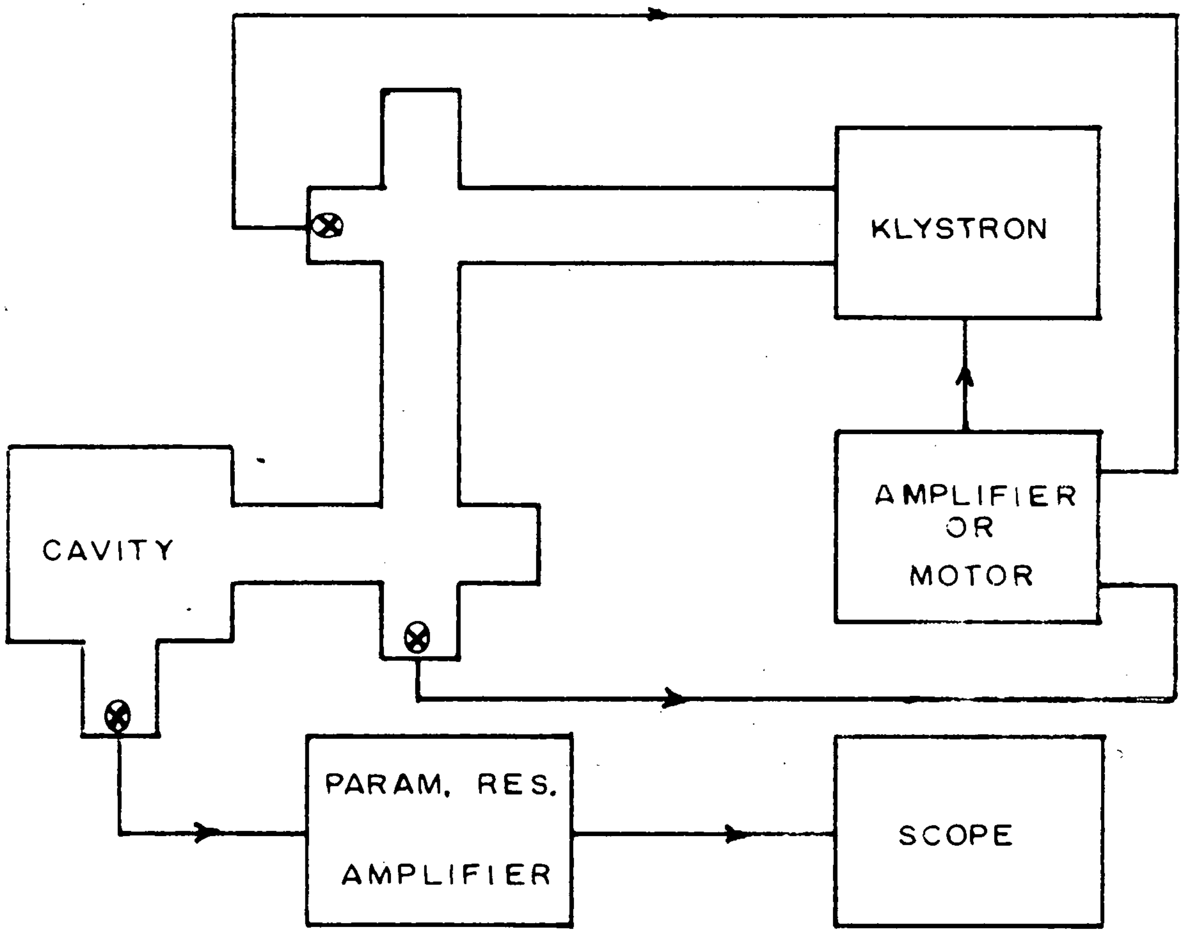
as shown by Pound. Γ_0 and m are constants of the circuit, δ is the phase shift of ν_a which depends on the length to the cavity and the frequency difference of $\nu_k - \nu_0$. It is this $\cos \delta$ which gives the required information to produce a positive or negative correction voltage. The voltage of ν_a detected at crystal A is then amplified and mixed in a phase sensitive detector with a reference signal from the same auxiliary oscillator. The output of the phase sensitive detector contains a D.C. component (see appendix A) which is the correction voltage applied to the reflector of the klystron.

The second and third variations of this A.C. method are shown in fig. 8 and 9. The method shown in fig. 8 modulates the resonant frequency of the cavity by vibrating some part of the cavity such as a diagram or some object placed in the cavity as a reed. The other method in fig. 9 modulates the frequency of the klystron. The operation of both these circuits is similar as it is only the difference $\nu - \nu_0$ which determines the D.C. correction voltage. The detailed operation of this circuit shall be left for chapter 3, but a sketch of its action is given now. Microwaves generated in the klystron enter the cavity. If an external load is used only a small amount need enter the stabilizing circuit. As the frequency of the microwaves or the resonant frequency of the cavity is modulated we can say that the difference $\nu - \nu_0$ is constantly changing, hence the amplitude of the output from the cavity is changing due to the resonance curve of the cavity. Moreover, the phase of this output will depend on the sign of $\nu - \nu_0$. This signal is detected, amplified, and compared in a phase sensitive detector with a signal from the same auxiliary oscillator. As shown in appendix A, there is a D.C. component in the output of the phase sensitive detector. This D.C. voltage is the correction voltage applied to the reflector of the klystron.

One may note a feature lacking in all the methods with the exception of the last two variations of the A.C. method. This particular feature is that the cavity is a transmission type as far as the regulating circuit is concerned so that one does not depend on reflections from the cavity.

2.6 Combination of Methods

In addition to these different methods, one can combine two, such as the servo-mechanical and say the Pound's A.C. methods as W.F. Gabriel and F.A. Jenks have successfully done (ref. 13, 14). We may note however, that as we now have two correcting systems or loops, there will be some balance frequency that does not coincide with the resonant frequency of the cavity. This combination of methods is a fairly good way of stabilizing the frequency of a microwave oscillator when one is interested in absolute stabilization, as the servo-mechanical method corrects for the slower variations while the



PROPOSED ADAPTION OF D.C. METHOD

FIG. 10

To be facing page 19

electronic method corrects for the faster variations. Further, the electronic method can act as an anti-hunt circuit for the servo-mechanical method. Gabriel used this combination in conjunction with the measurements of the dielectric of gases where an absolute frequency control is necessary. Because of this necessity, great effort was spent to assure that the resonant frequency of the cavity remained constant by minimizing the effects due to such factors as temperature and humidity fluctuations.

2.7 Feasibility of the Various Methods to the Present Problem

As stated previously the chosen method must be such that the stabilization action and paramagnetic resonance must not interfere with one another.

If it was attempted to use either of the D.C. methods the circuit would have to look something like that shown in fig. 10. Microwaves from the klystron find their way to the cavity, some then being reflected and some transmitted. Those transmitted through the cavity could be used for observing paramagnetic resonance and those reflected from the cavity could be used for the stabilizing circuit. There is, however, a serious fault that the reflection coefficient of the cavity is altered by the presence of a paramagnetic resonance. Thus if the regulation circuit is working so that $\nu = \nu_0$, and if one is changing the D.C. magnetic field so that a paramagnetic absorption occurs, the condition of no reflection is upset, hence the descriminator would have a D.C. output and the klystron would detune. Minor difficulties arise by the fact that not all the microwave energy reaches the cavity and a D.C. system is difficult to stabilize. We can therefore say that the D.C. system is not feasible for the present problem.

The absorption method is obviously not applicable for the klystron frequency is locked onto a constant frequency and not the varying resonant frequency of a cavity.

The A.C. method devised by Pound has a serious fault similar to that described for the D.C. method since Pound's A.C. method depends on reflections from the cavity. Another fault manifests itself by the presence of side bands in the cavity which would inconvenience paramagnetic resonance. Also, degenerative frequency modulation can occur by cancellation of I.F. in the microwave descriminator.

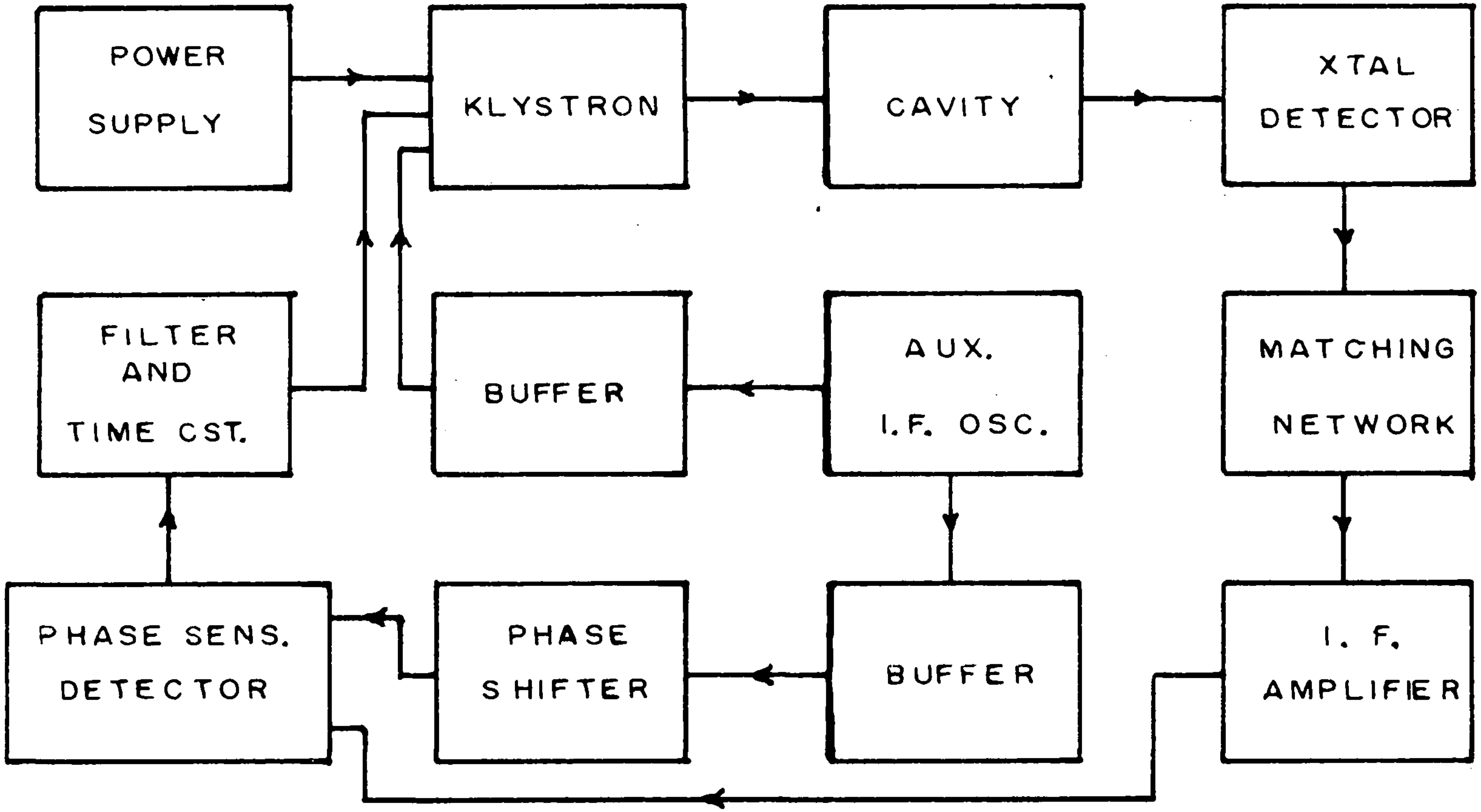
In comparison to the previous methods the A.C. methods involving frequency modulation of the klystron or cavity modulation do not contain any of the mentioned faults of the other methods. No use is made of any reflected microwaves, thus the presence of a paramagnetic absorption in the cavity doesn't affect the stabilization circuit. It may also be noted that the full amount of the microwave energy from the klystron enters the cavity. Another advantageous feature is that there is zero I.F. signal from the cavity when $\nu = \nu_0$, hence a high gain amplifier may be used. The frequency modulation method lends itself to the use of a higher searching frequency than the cavity modulation method. A high modulation frequency is desirable since information is collected more frequently than if a lower modulation frequency is used. Further, the cavity modulation method presents several mechanical difficulties not present in the frequency modulation method. Because of these reasons the frequency modulation method was chosen for frequency stabilization of the reflex klystron.

There are several minor disadvantages to this method which manifest themselves as only second order effects. They are the following.

(a) Since the frequency of the klystron is modulated, the klystron will work back and forth over a small part of the particular mode of operation. If a mode is carefully examined, it will be noted that there exist small jumps in the power output. These small jumps will manifest themselves in the form of noise introduced into the spectrometer.

(b) There is the possibility of the introduction of a magnetic pickup loop into the spectrometer when the frequency stabilization is in operation. However, this aspect exists for any type of stabilizer used.

(c) One would expect the modulation of the frequency itself to increase the error in the measurement of frequency at which paramagnetic resonance occurs; but this is not necessarily the case. The error of the frequency measurement without stabilization is of the order of (10 to 20) megacycles. Now with a cavity of a Q of 10,000 and an operating frequency of 25 kilo-mega cycles per second, one needs to sweep the frequency through a maximum of only 5 megacycles per second for successful operation of the stabilizing system. It can thus be seen that the error in the frequency measurements will not be increased by a noticeable amount.



DETAILED BLOCK DIAGRAM OF FREQUENCY MODULATION METHOD FOR FREQUENCY STABILIZATION FIG. 11

To be facing page 23

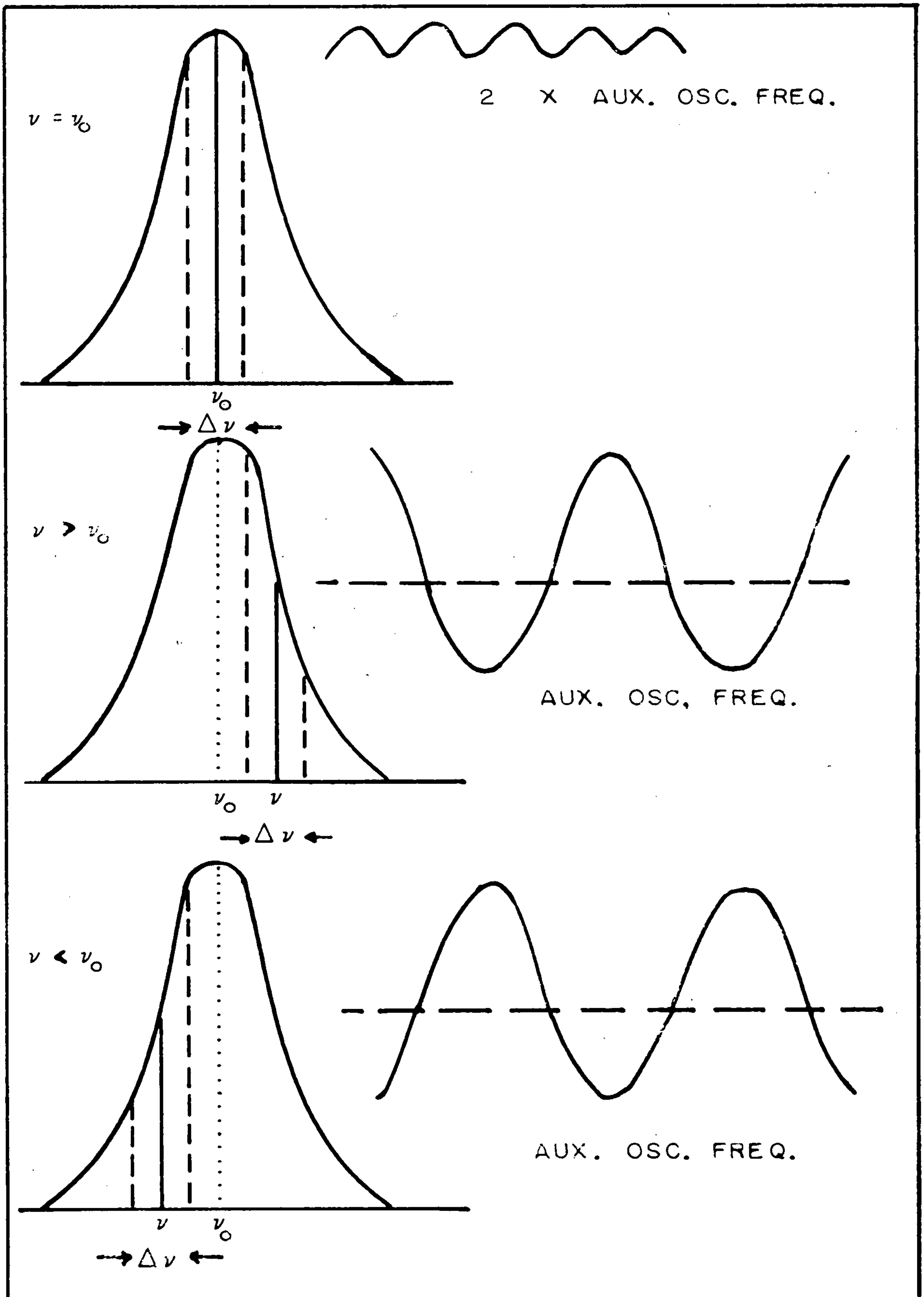
CHAPTER III

THE FREQUENCY MODULATION METHOD OF FREQUENCY STABILIZATION

Chapter II showed the superiority of the frequency modulation method for stabilizing the klystron. Such a stabilization circuit was built. In this chapter the operation of such a system is presented. A description of the circuits built is also given.

3.1 Operation of the Circuit

A detailed block diagram of the stabilization system is shown in fig. 11. An auxiliary oscillator provides a signal which is applied to the reflector of the klystron thereby frequency modulating the output. A buffer section isolates the auxiliary oscillator and klystron. The frequency modulated microwaves enter the cavity which essentially converts the frequency modulation to an amplitude modulation. This amplitude modulation is detected by a crystal detector. The detected signal is illustrated in fig. 12. The frequency modulation of the microwaves changes the frequency in the cavity by an amount $\Delta\nu$ at a rate equal to the frequency of the auxiliary oscillator. As the amplitude of the microwaves or in other words the envelope follows the shape of the cavity resonance curve, we can see that if the frequency of the klystron equals the resonant frequency ν_0 of the cavity, we then obtain a detected



DETECTED SIGNAL FROM CAVITY

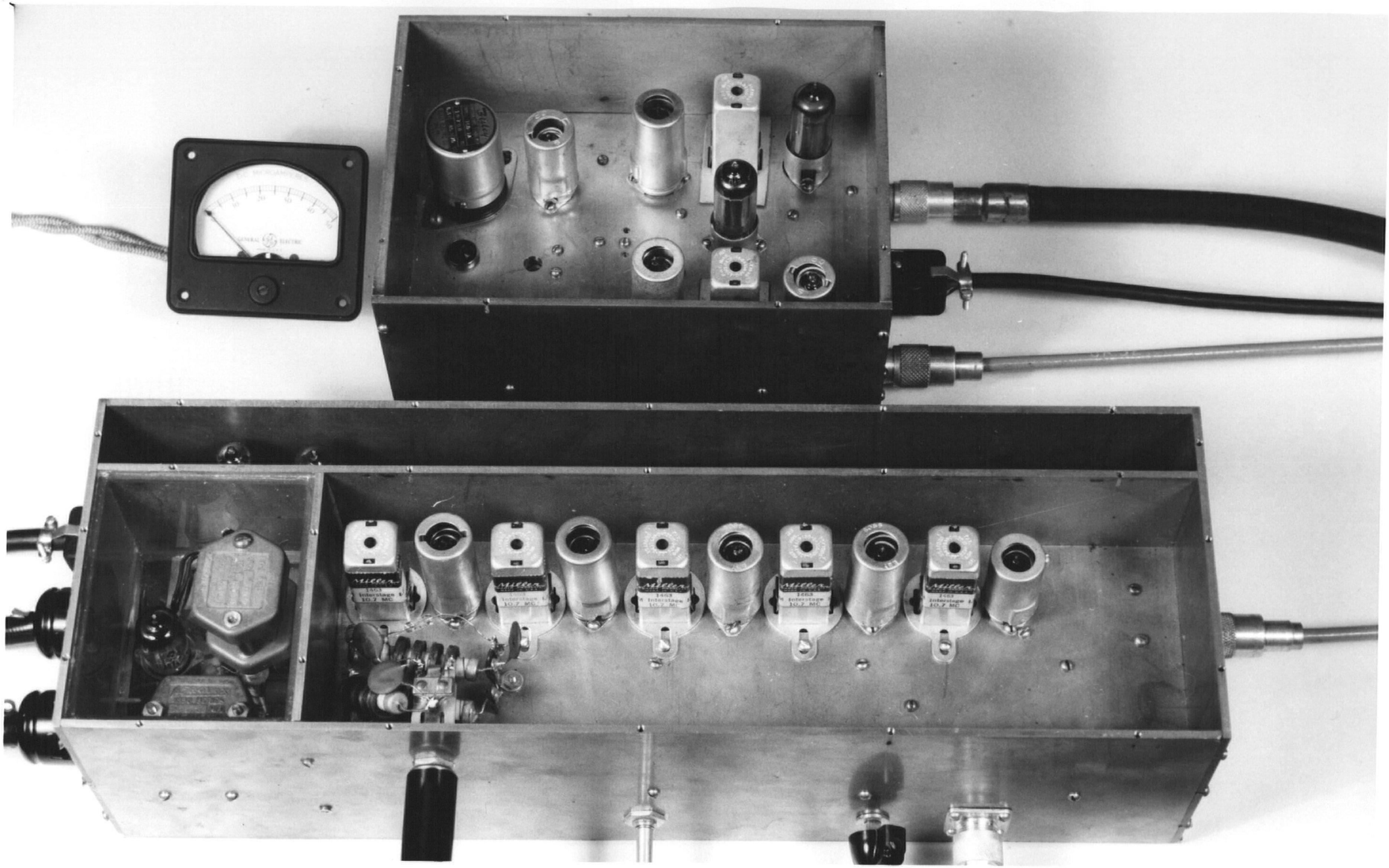
FIG. 12

To be facing page 24

signal at a frequency double that of the auxiliary oscillator. If $\nu < \nu_0$, we then get a detected signal at a certain phase and at the auxiliary oscillator frequency; if $\nu > \nu_0$, we obtain a detected signal 180° out of phase with the $\nu < \nu_0$ case, which can easily be seen by considering fig. 12. If the frequency is increasing then for $\nu > \nu_0$ the signal has a negative slope, while for $\nu < \nu_0$ it has a positive slope. Thus the phase of the detected signal gives us the information as to whether a positive or negative D.C. correction voltage is required.

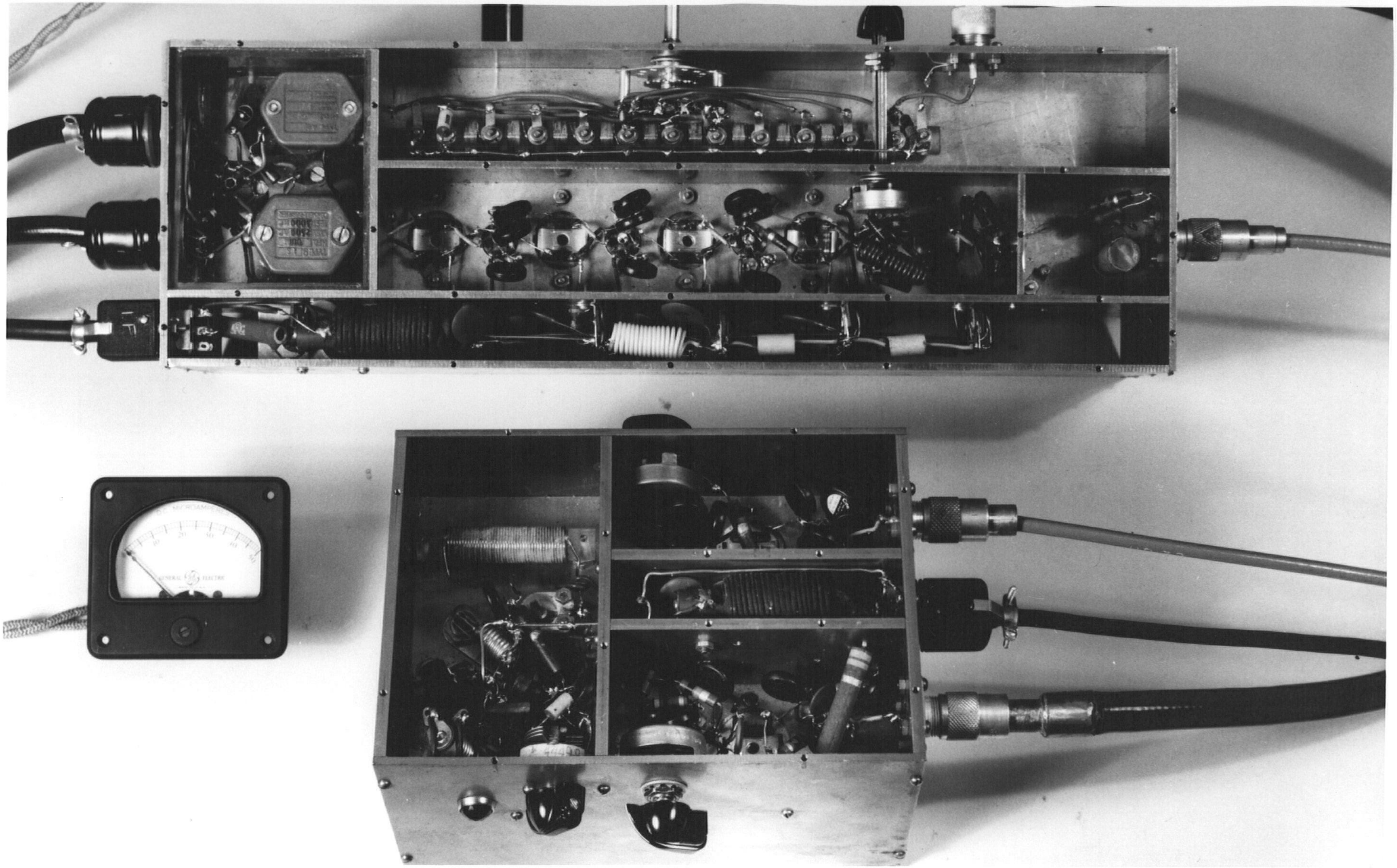
The detected signal is amplified, after passing through a matching section and enters a phase sensitive detector. To perceive a change in phase of this signal, the phase sensitive detector must have a reference signal from the same auxiliary oscillator. This is supplied via a buffer section and a phase shifting network. The phase shifting network allows adjustment of relative phases so that maximum D.C. correction signal is obtained in the output of the phase sensitive detector as the amplitude of this D.C. component involves a $\cos \delta$, δ = phase difference between the two signals (see appendix A). A low pass filter cuts out all the A.C. components in the output of the phase sensitive detector while a network giving a time constant determines the time response of the complete circuit. The D.C. correction voltage is then applied to the reflector of the klystron so that $|\nu - \nu_0|$ is lessened or ν is brought closer to ν_0.

Plate III



To be facing page 25 Top View of the Frequency Stabilizing System

Plate IV



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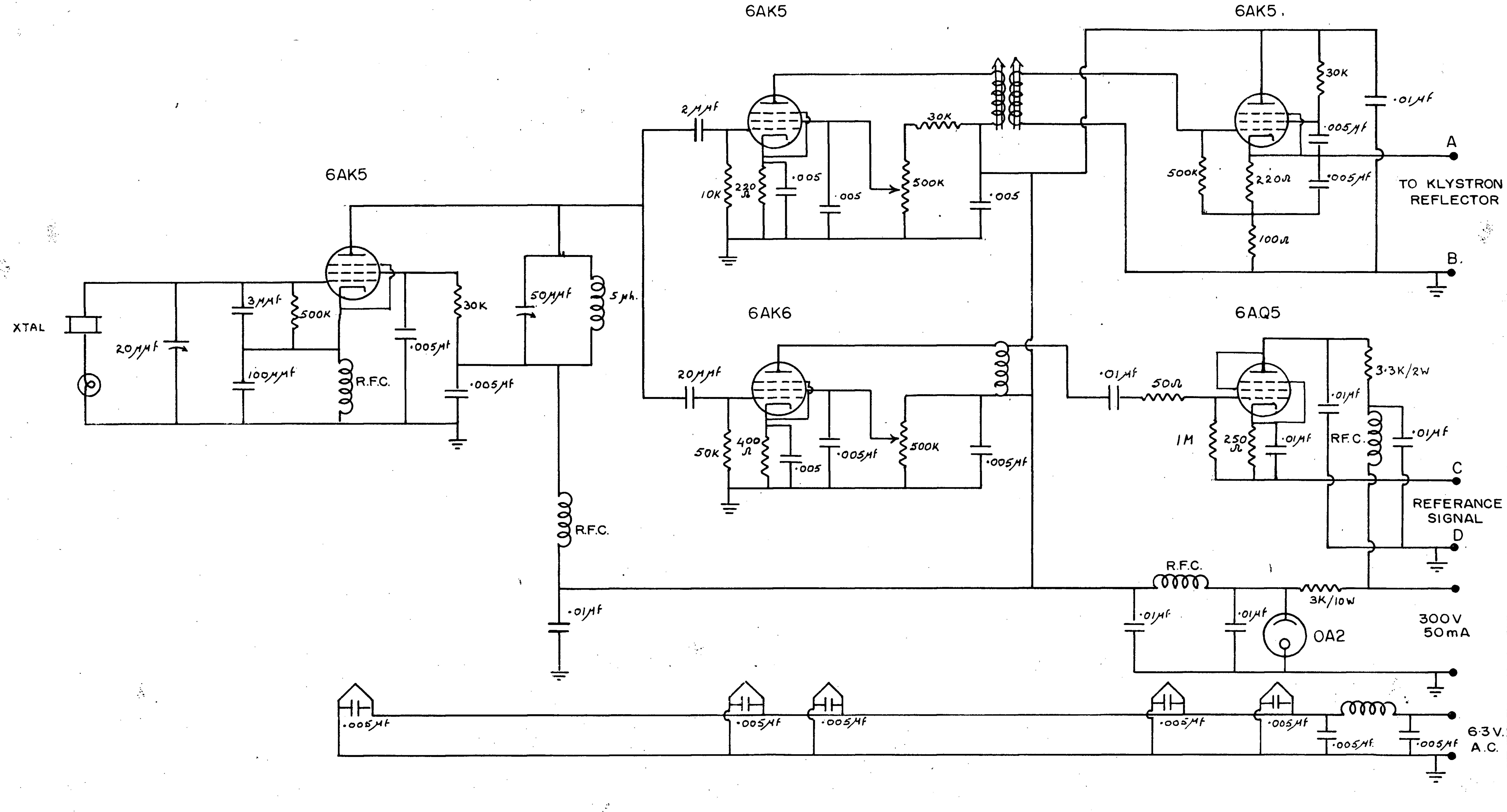
Bottom View of the Frequency Stabilizing System

It can be noticed that there is no D.C. correction voltage when ν is at a position where the slope of the cavity resonance curve is zero. Thus if $\nu = \nu_0$, then there is no correction voltage, also if ν jumps in the region where the cavity resonance curve has zero amplitude, then again there is no D.C. correction voltage. This behaviour shows that a correction to the frequency ν only occurs for frequency fluctuations which remain on the cavity resonance curve.

3.2 Circuitry

The circuitry of the individual components in the block diagram will now be described. The complete circuit is contained in three chassis. The auxiliary oscillator and buffer sections were put in one chassis (smaller chassis in Plate III IV) while the matching network, I.F. amplifier, phase sensitive detector and phase shifting network were put in a second chassis (Larger chassis in Plate III and IV). The low pass filter and time constant were placed in the "klystron box" which, as its name suggests, contains the klystron. All components were shielded with brass so that 500 kilcycles used elsewhere in the spectrometer would not interfere with the frequency regulating circuit. Further shielding of individual components also was employed.

The auxiliary oscillator is a 10.7 megacycle per second crystal oscillator giving high frequency stability, as a change in the frequency of the auxiliary oscillator would



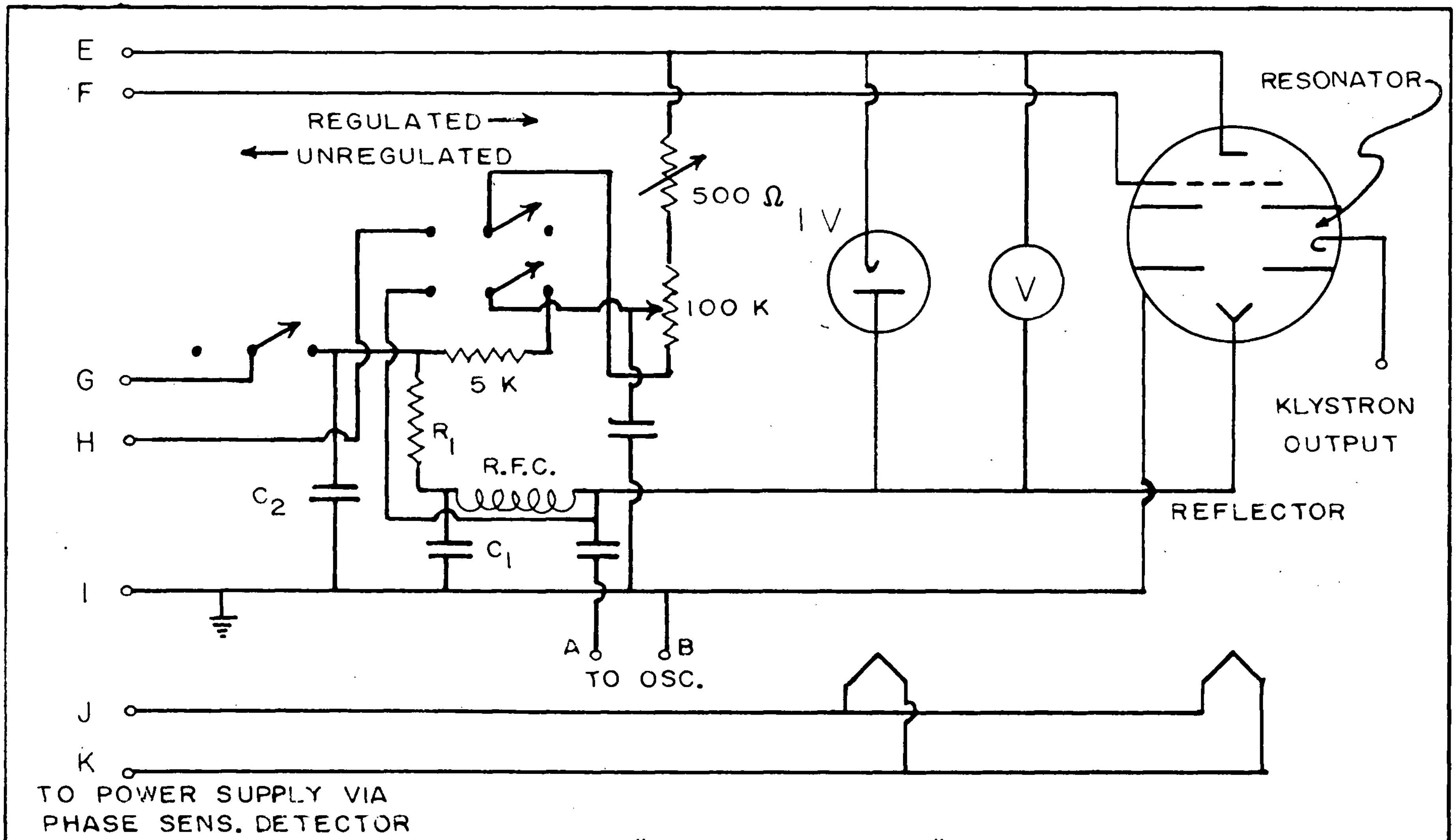
CIRCUIT OF OSCILLATOR AND BUFFER SECTIONS FIG. 13

CIRCUIT OF MATCHING NETWORK, AMPLIFIER, PHASE SENS. DETECTOR AND PHASE SHIFTER FIG. 14

present a spurious phase change at the phase sensitive detector. The buffer sections consist of a low gain amplifier stage followed by a cathode follower for driving the signal through cables. The circuit is shown in fig. 13, (ref. 15, 16).

The crystal detector is a 1N26 located in the wave guide. The matching network is a Robert's network (ref. 17) designed to present a non reactive impedance to the crystal detector. The I.F. amplifier is a broad band, five stage tuned amplifier with a gain of about 10^6. The phase sensitive detector consists of a dual control pentode, a 6AS6 at the D.C. voltage of the klystron's reflector. The phase shifter for the reference signal consists of a variable, lumped parameter, delay line designed to give a maximum of 180° phase shift (ref. 18). For further phase shift one can shift the phase of the signal in the amplifier by interchanging two leads on an I.F. transformer. The phase can be obtained to within 10° of the maximum adjustment; this is sufficient as the $\cos \delta$ function is fairly unsensitive to angular dependence when $\delta \approx 0$. The circuit is shown in fig. 14.

Other phase sensitive detectors such as a diode bridge circuit or a 6BE6 as a dual control pentode were tried, however the 6AS6 was found to be the most satisfactory. For the phase shifter, R.C. networks were tried but found unsatisfactory at I.F. frequencies, due to stray capacities.



CIRCUIT OF "KLSTRON BOX"

FIG. 15

To be facing page 27

The circuit of the klystron box is shown in fig. 15. The time constant of the frequency regulating circuit is determined by R_1 and C_1 while the condensor C_2 acts as the filter for the A.C. components in the output of the phase sensitive detector.

The leads from the power supply for the klystron enter the chassis containing the phase sensitive detector and then enter the klystron box which contains the shielded klystron.

The klystron power supply circuit is shown in fig. 16 and the circuit of the power supply for the amplifier, oscillator and buffer sections is shown in fig. 17.

CHAPTER IV.

THE PERFORMANCE OF THE FREQUENCY STABILIZATION SYSTEM

In this chapter the performance of the circuits described in chapter III is discussed, a few simple calculations are made to illustrate its operation. Experimental performance is also given.

4.1 Some Calculations

One may consider the frequency stabilizing circuit to be basically as shown in fig. 18. It is shown just as a feedback loop. Due to limitations of the apparatus, the frequency

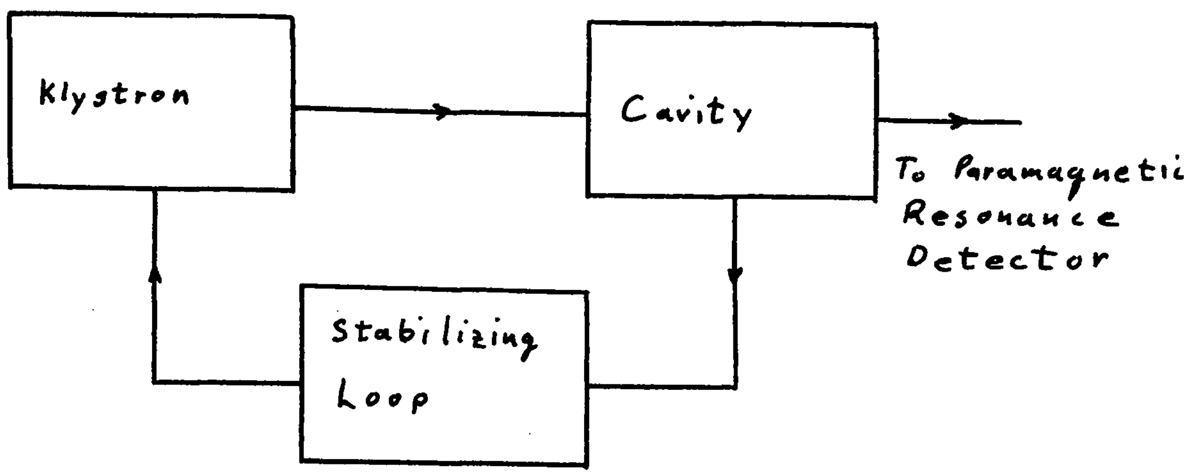


Figure 18

ν of the klystron will not equal the resonant frequency ν_0 of the cavity.

If we define

G = the gain of the feedback loop and the cavity (volts/frequency)

$d\nu$ = an original frequency deviation of ν from ν_0 before stabilization

$d\nu'$ = the frequency deviation of ν from ν_0 after stabilization

T = sensitivity of klystron reflector (frequency/volts)

then $G\,d\nu'$ is the residual correction voltage. The resultant residual frequency deviation is the unstabilized $d\nu$ minus the change towards ν_0 caused by the applied error voltage ie.

$$d\nu' = d\nu - TG\,d\nu' \quad \text{or} \quad \frac{d\nu'}{d\nu} = \frac{1}{1+TG} = \frac{1}{S} \quad - - - - \ (1)$$

S being the stabilization factor. We can now see that the loop is essentially one of negative feedback.

To illustrate the performance of this loop, one can calculate the tendency to correct an initial frequency deviation $d\nu$ of ν. If V is the amplitude of the 10.7 megacycles per second applied to the reflector of the klystron, then the frequency modulation of the microwaves will have an amplitude of $\frac{\Delta\nu}{2} = \frac{TV}{2}$; $\Delta\nu$ being the total frequency sweep.

It is now assumed that the resonance curve of the cavity has a guassian shape. This assumption is reasonable for these calculations since only approximations are attempted. Actually the shape of the cavity resonance curve is not important as the Q of the cavity is high and we are not interested in the shape of the tail of the curve.

On the gaussian assumption, it can be shown that the cavity resonance curve will have a shape defined by the following.

$$B(\nu) = B(\nu_0)\, e^{-c(\nu-\nu_0)^2} \quad ; \; c = \frac{(2\ln 2)Q^2}{\nu_0^2} \qquad \text{- - - -} \; (2)$$

$B(\nu)$ is defined as the square root of the power level of the microwave at the crystal detector. This definition takes account of the cavity resonance and any attenuation present between the cavity and crystal detector. $B(\nu_0)$ then is the square root of the power level of the microwaves at the crystal detector when at the peak of the cavity resonance curve.

When the kylstron frequency is modulated

$$\nu = \frac{\Delta\nu}{2} \sin \omega t + \nu_0 + d\nu$$

where $d\nu = \overline{\nu - \nu_0}^{\,time}$, the error which is to be corrected. The output from the cavity in terms of the square root of power is then

$$F(\nu) = B(\nu_0)\, e^{-c\left(d\nu + \frac{\Delta\nu}{2}\sin\omega t\right)^2}$$
$$= B(\nu_0)\, e^{-c\,d\nu^2 - c\,d\nu\,\Delta\nu \sin\omega t - \frac{c}{4}\Delta\nu^2 \sin^2\omega t}$$

If $F(\nu)$ is written in a fourier series and the coefficient of the $\sin\omega t$ term is calculated, the amplitude of the 10.7 megacycle component leaving the cavity is obtained. This amplitude is given by

$$F_\omega(\nu) = \frac{1}{\pi}\int_0^{2\pi} F(\nu) \sin\omega t \; d(\omega t)$$
$$= \frac{B(\nu_0)}{\pi}\, e^{-c\,d\nu^2} \int_0^{2\pi} e^{-c\,d\nu\,\Delta\nu \sin\omega t - \frac{c\Delta\nu^2}{4}\sin^2\omega t} \sin\omega t \; d(\omega t)$$

As shown in Appendix B, for $\Delta\nu^2 < \frac{1}{c}$ and $d\nu < \frac{1}{c\,\Delta\nu}$ an approximation can be made to $F_\omega(\nu)$ which is almost identical to the simplification that

$$F_\omega(\nu) \simeq F'_\omega(\nu) = \frac{1}{2}\left| B\left(\nu_0 + \frac{\Delta\nu}{2} + d\nu\right) - B\left(\nu_0 - \frac{\Delta\nu}{2} + d\nu\right)\right|$$
$$= B(\nu_0)\, e^{-c\left[d\nu^2 + \left(\frac{\Delta\nu}{2}\right)^2\right]} \sinh\left(-c\, d\nu\, \Delta\nu\right) \text{ ---- } (3)$$

It is experimentally known that the crystal detector detects this signal according to a square law. Thus, after amplification of the detected signal, we obtain a voltage of

$$E_2 = k F_\omega^2 A \quad - - - - - - - - - - - (4)$$

$A =$ the amplification of the I.F. amplifier

$k =$ the proportionality constant for the crystal detector.

This is the voltage entering the phase sensitive detector which is out of phase by an amount δ with the reference voltage E_1. Appendix A shows that the D.C. output of the phase sensitive detector is given by

$$i_{D.C.} \approx \frac{1}{2} g_1 E_1 E_2 \cos\delta \quad - - - - - - - - - - (5)$$

where

$g_1 =$ the conversion transconductance

The D.C. correction voltage is given by

$$W = i_{D.C.} R_L \quad - - - - - - - - - - (6)$$

where

$R_L =$ the load resistance of the phase sensitive detector.

Thus the tendency to correct $d\nu$ is

$$\delta\nu = WT = i_{D.C.} R_L T \quad - - - - - - (7)$$

Combining equations 2,3,4,5,6,7, we find that

$$\delta\nu = \frac{1}{2} g_1 E_1 E_2 \cos\delta \, R_L T$$

$$= \frac{kA}{2} g_1 E_1 R_L T \, B^2(\nu_0) \cos\delta \, e^{-2c\left[d\nu^2 + \left(\frac{\Delta\nu}{2}\right)^2\right]} \sinh^2(+c\, d\nu \Delta\nu) \quad (8)$$

$\delta\nu$ is a measure of the "force" pulling the klystron frequency towards the cavity resonant frequency. This force tends to increase or decrease the frequency depending whether $\cos \delta$ is positive or negative.

Equation 8 shows that if the error $d\nu$ is large or zero, then the tendency for correction is zero. Actually, in accordance with equation 1, the stabilizing system reduces $d\nu$ to $d\nu'$ in absolute values. When the error is $d\nu'$, the tendency towards correction is balanced by the "stiffness" or the reaction of the loop against correction.

It may be noted that these calculation have assumed that the circuit regulates immediately, i.e. that the time constant of the loop is zero. In practice, a time constant is used which will modify the expressions obtained. The time constant actually prevents hunting and has a smoothing action to the corrections.

4.2 Experimental Performance

The stabilization loop managed to lock the klystron frequency to the cavity resonance frequency to a fairly good degree. Two limiting factors were found in the stabilizing system. Blocking can occur in the high gain amplifier, if the crystal is run at a high level or if sufficient attenuation isn't present in the μ-wave circuit. Pickup can occur in the high gain amplifier. This pickup originates, in spite of complete shielding, from the reference voltage phase shifter contained in the same chassis as the amplifier. Hence, the magnitude of the reference voltage and the gain of the amplifier cannot both be a maximum value simultaneously.

Direct frequency measurements could not be made, however the order of magnitude of the quantities calculated in section (4.1) can be estimated if a reasonable Q value of 10^4 is assumed for the μ-wave cavity. Further the klystron oscillates at about 25 kilo-megacycles.

The long term frequency stability over a period of a few hours (a test was made over four hours) is sufficient to cause the amplitude of the microwaves leaving the cavity to be reasonably constant, the changes present can be ascribed to the mode of oscillation in the klystron. This action implies that the stabilization factor of the regulating loop is of the order of 20 or higher i.e. $\frac{d\nu'}{d\nu} = \frac{1}{20}$. For a resonance curve at 25 kilo-megacycles, and a Q of 10^4, $d\nu$ can be up to 2 megacycles and still be on the resonance curve. If $d\nu'$ is 100 kilocycles or less then the amplitude of the microwaves leaving the cavity will be fairly close to the maximum value.

The various parameters in equation 8 of (4.1) were measured. They were found as follows. The crystal constant $K = 15\ \mathrm{amp}^{-1}$. This value was measured with a 30 megacycle wave modulated at 1000 cycles. The easy assumption is made that K has the same value at microwave frequencies. The klystron reflector sensitivity T is 100 kilocycle/volt. $B(\nu_0)$ is taken as $5\times10^{-3}\ (\mathrm{watts})^{\frac{1}{2}}$ since about 25 microwatts of power are at the crystal detector, $g_1 E_1$ is about 2500 micromhoes, R_L is $20\,K\Omega$, the amplitude of the klystron modulation signal is $2\sqrt{2}$ volts while the reference voltage is seven volts.

Equation 8 then becomes, with $\cos\delta = \pm 1$ $\left(\cos\delta = \frac{-d\nu}{|d\nu|}\right)$

$$\delta\nu = 9.43\times 10^{8} \exp\left[-.444\cdot 10^{-12} d\nu^2\right] \sinh^2\left[.063\cdot 10^{-6} d\nu\right]$$

Thus if $d\nu$ is 500 kilocycles, the correction tendency is 686 kilocycles or if $d\nu$ is one megacycle, the correction tendency is 2.57 megacycles.

A good test of the control of the stabilizing loop is its action when the reflector voltage control is changed manually. It is found that the stabilizing loop manages to lock the reflector voltage, and the frequency of the klystron, so that the manual control makes no difference over a large range.

In conclusion, the frequency of the klystron has been stabilized to at least one part in $2.5.10^5$ to the resonant frequency of the cavity used for paramagnetic resonance. This frequency stability, if present with magnetic field stability, makes it possible to use the spectrometer as a narrow band instrument, thereby increasing the sensitivity by a factor of about 100;

APPENDIX A

If two signals at the same frequency are fed into a phase sensitive detector, then there is a D.C. component in the output.

Let the two signals be $E_1 \sin \omega t$ and $E_2 \sin(\omega t+\delta)$. In a phase sensitive detector there exists some type of non-linearity present. Let it be assumed that the type of non-linearity present is as follows:

$$g = g_0 + g_1 E_1 \sin \omega t + g_2 (E_1 \sin \omega t)^2 + \cdots + g_n (E_1 \sin \omega t)^n + \cdots \quad (1)$$

where g is the total transconductance of the detector shown to $E_2 \sin(\omega t+\delta)$.

It is known that the output current is

$$i = E_2 g \sin(\omega t + \delta) \quad - - - - - - - - \quad (2)$$

upon substitution of (1) into (2)

$$i = E_2 g_0 \sin(\omega t+\delta) + g_1 E_1 E_2 \sin \omega t \sin(\omega t+\delta) + \cdots + g_n E_1^n E_2 \sin^n \omega t \sin(\omega t+\delta) + \cdots \quad - - \quad (3)$$

It can be shown that

$$\sin \omega t \sin(\omega t+\delta) = \frac{\cos\delta}{2} - \frac{\cos\delta}{2} \cos 2\omega t + \frac{\sin\delta}{2} \sin 2\omega t \quad - - \quad (4)$$

upon substitution of (4) into (3)

$$i = \left[g_1 E_1 E_2 + \frac{g_3}{4} E_1^3 E_2 + \cdots + \frac{g_{2n+1} E_1^{2n+1} E_2}{2^{2n}}\right] \frac{\cos\delta}{2} + a_1 \cos \omega t + \cdots + a_n \cos n\omega t + \cdots \quad - - - - - \quad (5)$$

where a_k $(k = 1, 2, \cdots n)$ are coefficients of the A.C. components.

It can be seen that there exists a D.C. component varing as the cosine of the phase difference δ between the two signals, given by the first term of (5). It is considered that only the first order term is important in this D.C. component. The D.C. current is then given by equation (6).

$$i_{D.C.} \approx \frac{1}{2} g_1 E_1 E_2 \cos \delta \quad - - - - - - - \quad (6)$$

g_1 is known as the conversion transconductance.

APPENDIX B

Consider the integral for a and b < 1.

$$I = \frac{B(\nu_0)}{\pi} e^{-c d\nu^2} \int_0^{2\pi} e^{-a \sin x - b \sin^2 x} \sin x \, dx \quad --- \quad (1)$$

where

$$a = c\, d\nu\, \Delta\nu$$
$$b = \frac{c\, \Delta\nu^2}{4}$$
$$x = \omega t$$

As a and b < 1, the exponential factor can be written as a series as the following

$$e^{-a \sin x - b \sin^2 x}$$
$$= 1 - a \sin x + \left(-b + \frac{a^2}{2!}\right)\sin^2 x + \left(\frac{2ab}{2!} - \frac{a^3}{3!}\right)\sin^3 x$$
$$+ \left(\frac{b^2}{2!} - \frac{3a^2 b}{3!} + \frac{a^4}{4!}\right)\sin^4 x + \left(\frac{-3ab^2}{3!} + 4\frac{a^3 b}{4!} - \frac{a^5}{5!}\right)\sin^5 x$$
$$+ \left(-\frac{b^3}{3!} + 6\frac{a^2 b^2}{4!} - 5\frac{a^4 b}{5!} + \frac{a^6}{6!}\right)\sin^6 x + \left(4\frac{ab^3}{4!} - \frac{10}{5!}a^3 b^2\right.$$
$$\left. + 6\frac{a^5 b}{6!} - \frac{a^7}{7!}\right)\sin^7 x + \cdots \quad ——— \quad (2)$$

hence

$$I = \frac{B(\nu_0)}{\pi} e^{-c\, d\nu^2} \int_0^{2\pi} \sum_{p=1}^{\infty} C_p \sin^p x \, dx \quad ——— \quad (3)$$

where C_p is given by (2)

Further as

$$\int_0^{2\pi} \sin^n x \, dx = \begin{cases} \frac{(n-1)(n-3)\cdots 1}{n(n-2)(n-4)\cdots 2} \cdot 2\pi & ; n \text{ even} \\ 0 & ; n \text{ odd} \end{cases}$$

then

$$I = \frac{B(\nu_0)}{\pi} e^{-c d\nu^2} \, 2\pi \sum_{p=2}^{\infty} C_p \frac{(p-1)(p-3)\cdots 1}{p(p-2)(p-4)\cdots 2} \quad ; p \text{ even}$$

since a and b < 1 the first few terms will give a good approximation.

Consider the terms up to p=8.

$$I = B(\nu_0)e^{-c\,d\nu^2}\Big[-a + \frac{3}{4}ab - \frac{a^3}{8} - \frac{5}{16}ab^2 + \frac{5}{48}a^3b - \frac{a^5}{24\cdot 8} + \frac{35}{128}ab^3 - \frac{35}{6\cdot 128}a^3b^2\Big]$$

If one considers the terms up to the third power, then

$$I = B(\nu_0)\,e^{-c\,d\nu^2}a\Big[-1 + \frac{3}{4}b - \frac{a^2}{8} - \frac{5}{16}b^2\Big] \quad --\ (3)$$

Now consider the expression

$$F_w'(\nu) = \frac{1}{2}\left|B\left(\nu_0 + \frac{\Delta\nu}{2} + d\nu\right) - B\left(\nu_0 - \frac{\Delta\nu}{2} + d\nu\right)\right|$$

$$= +B(\nu_0)\,e^{-c\,d\nu^2}e^{-b}\sinh a \quad ---\ (4)$$

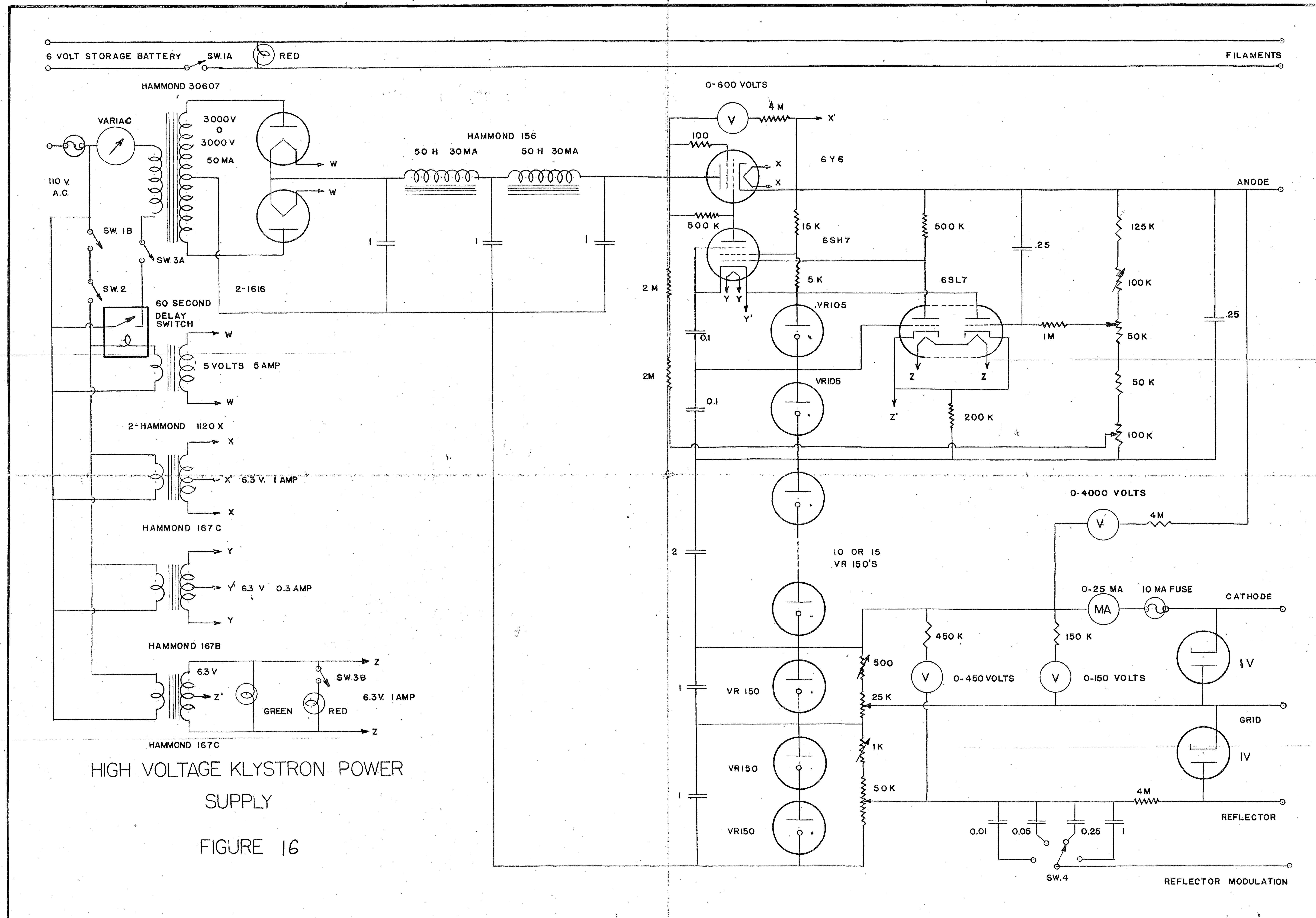
If e^{-b} sinh (a) is written in a series, and only terms up to the third power are considered, the following is obtained.

$$F_w'(\nu) = B(\nu_0)\,e^{-c\,d\nu^2}a\Big[-1 + b - \frac{1}{6}a^2 - \frac{1}{2}b^2\Big] \quad ---\ (5)$$

It can be noted that F as given by (5) is a reasonable approximation to I as given by (3). It can then be said that the following approximation is valid for a and $b < 1$

$$\frac{B(\nu_0)}{\pi}e^{-c\,d\nu^2}\int_0^{2\pi} e^{-a\sin x - b\sin^2 x}\sin x\,dx$$

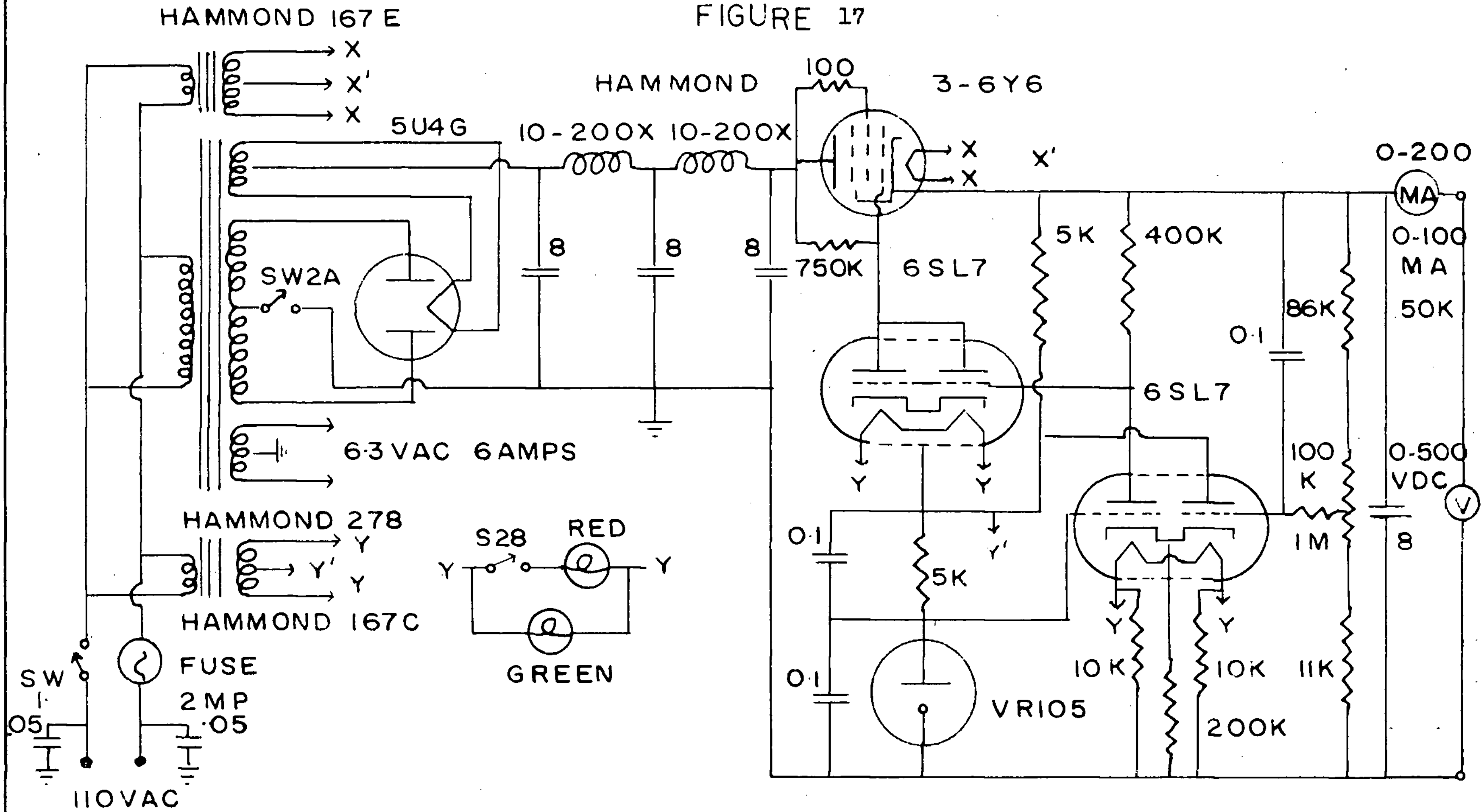
$$\approx \frac{1}{2}\left|B\left(\nu_0 + \frac{\Delta\nu}{2} + d\nu\right) - B\left(\nu_0 - \frac{\Delta\nu}{2} + d\nu\right)\right|$$



HIGH VOLTAGE KLYSTRON POWER SUPPLY

FIGURE 16

FIGURE 17



TYPICAL LOW RIPPLE, HIGH REGULATION POWER SUPPLY

250-375 VOLTS D·C· 25-200 MA

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