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INSTRUMENTATION FOR CONTINUOUSLY RECORDING
PLASMA-INDUCED FREQUENCY SHIFTS OF TWO
MICROWAVE CAVITY RESONANCES

Technical Report

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Provo, Utah

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MASTER

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INSTRUMENTATION FOR CONTINUOUSLY RECORDING
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M.S. Degree, April 1974

ABSTRACT

Instrumentation has been developed for the continuous recording of the frequency shifts of two resonances of a spherical microwave cavity. These changes in the resonant frequency are caused by the presence of a plasma in an electrostatic confinement system. To detect the frequency shifts, a digitally controlled sample-and-hold circuit is employed which senses the resonances of the cavity in the two states, "plasma" and "no plasma." The two states are controlled by high voltage, applied to the inner sphere of the confinement system, which is line-synchronously switched on and off with a vacuum switch.

Tests of the system, with quiet operation, show that shifts of the order of two parts in 10^6 can be detected by this method.

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MICROWAVE CAVITY RESONANCES

A Thesis
Presented to the
Department of Physics and Astronomy
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In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Robert Pugmire Evans
April 1974

This thesis, by Robert P. Evans, is accepted in its present form by the Department of Physics and Astronomy of Brigham Young University as satisfying the thesis requirement for the degree of Master of Science.

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I. INTRODUCTION

In the mid-1950's Philo T. Farnsworth suggested a method of plasma confinement and concentration using a dynamically produced potential well. In 1959 the I.T.T. Industrial Laboratories started a research program, under Farnsworth's direction, which investigated the inertial confinement concept. The principles of this approach and results of a series of experiments done at I.T.T. were reported by Robert L. Hirsch.¹ The research at Brigham Young University employs a vacuum envelope used by Hirsch and utilizes a similar electrode geometry. The inner electrode can serve also as resonant cavity in which weak rf fields are used to obtain information about the operation of the device without influencing its operation. It was for this purpose that the instrumentation described here was developed.

The Confinement Device

The confinement device (Figs. 1 and 2) consists of a highly-negatively-charged spherical electrode (a "cathode") enclosed by a grounded spherical anode. Six ion guns, mounted on the anode (Fig. 2), supply radial ion beams.

With the device in operation, high negative voltage applied to the hollow inner electrode (a spherical shell

Fig. 1. Diagram of the Confinement Device

A. The Confinement Device
(Showing Position of the High
Voltage Switch).

B. The Confinement Device
with Its Power Supplies.

Fig. 2. The Confinement Device.

A. The Commercial Units Used in the Frequency Shift Detection Circuits.

B. Sanborn Recorder with Digital Circuits Mounted on Lower Panel.

Fig. 3. Two Views of the System.

with small apertures) causes the ion beams to be accelerated radially inward. The converging ion beams substantially modify the otherwise uniform potential within the hollow sphere. The resulting electric field influences (and is influenced by) the electrons that are produced from ionization of the background gas (by ion-neutral collisions) and from secondary emission by ion collision with the inner wall of the shell. As a net result, the electrons tend to accumulate most at preferred regions within the cavity. When the high voltage is turned off, the charge distributions (electrons and ions) eventually decay.

The Problem

To sense the presence of the electrons, microwaves are introduced into the cavity. The detection of the electrons is actually an indirect method of making some inferences regarding the behavior of the ions. The spatial distribution of the ions would be of more direct interest than that of the electrons, but because of the magnitude of their mass relative to that of the electrons, they have negligible effect on the microwave fields. It is possible to make inferences regarding the distribution of the ions by sensing the distribution of the electrons since the electrons respond to the electric field which in turn depends on the spatial distributions of both the ions and the electrons.

Microwaves in a cavity form standing waves at the resonant frequencies which are determined by the cavity

geometry. When low densities of free electrons are present, the oscillating electric fields of the microwaves cause the electrons to oscillate which in turn induces a small upward change in each resonant frequency (i.e., it causes a "shift" of each resonant mode to a higher frequency). To measure this small frequency shift of a particular resonance in a "continuous" manner, as operating parameters are slowly changed, it is possible to repeatedly scan the resonance pattern in both the high voltage "on" and "off" conditions and develop a "dc" signal that is proportional to the frequency shift. If the frequency shifts are measured for two or more modes, having different radial variations of the amplitude of the microwave electric field, it is possible to derive information about the radial distribution of the electrons since each frequency shift is proportional to the (spatially) integrated product of the electron density and the square of the amplitude of the microwave electric field of that mode. The frequency shift, Δf , of a cavity resonant frequency f , is given by²,

$$\Delta f / f \approx \frac{1}{2} \int_p n/n_{co} E^2 dv / \int_c E^2 dv$$

where E is the microwave electric field, n is the electron density, $n_{co} (= m \epsilon_0 4 \pi^2 f^2 / e^2)$ is the cut-off electron density and where p and c indicate integration over the plasma region and the entire cavity respectively. This approximation applies when the electron collision frequency

is much less than the microwave frequency and $n \ll n_{co}$.

During operation of the device, temperature changes of the sphere cause changes in its dimensions due to thermal expansion which in turn causes drifts in the microwave resonance frequencies that can be much larger than the frequency shifts of interest. Frequency drifts of approximately 20 MHz at a resonant frequency of about 10 GHz (corresponding to a temperature change of approximately 100 centigrade degrees) have been seen.³ This is about twice as great as the largest frequency shifts expected as a result of the plasma presence. The temperature change is due to the energy of the incoming ions that is imparted to the cavity by collisions of the ions with the cavity walls. Fortunately the thermal changes are slow and their contribution to the frequency shift between "on" and "off" conditions can be made negligible by using a switching period that is short with respect to the thermal response time and yet long with respect to the build-up or decay of the electron population. The times required for build-up and for decay of the plasma depend on various parameters such as the ion energy, the ion transit time, the background pressure, and the secondary electron emission coefficient of the shell. Previous tests on the device indicated that these times are much shorter than a power-line period. Because the system is sensitive to various operating parameters, a continuous observation of that portion of the frequency shifts attributable only to the presence of the electrons is needed. This can then be

recorded simultaneously with the pressure, high voltage, current, and any other operating parameters desired.

Previous Results

During the summer of 1972, the device was put into operation at Brigham Young University. The device was operated with deuterium and the initial results of the work done were reported as follows:

Microwave observations to date have consisted primarily of simultaneous measurements of the shifts of the $TM_{4,1,0}$ mode and the $TE_{1,8,N}$ mode as the high voltage (of the ion gun power supply) is turned on or off.

Examples of the resonance shift are shown in Fig. 1 [reproduced as Figure 4 in this thesis]. The microwave input was swept linearly from 10.4 to 11.0 GHz at a rate of 60 sweeps per second and appropriate portions of the sweep (near 10.7 and 10.9 GHz) were displayed on the two traces of a Tektronix 564 storage oscilloscope. Multiple traces were integrated over a period of approximately two seconds straddling the time of voltage turn-off. The sweep speed corresponds to approximately 2.2 MHz per cm on the scope trace. A frequency marker of the sweeper can be seen near the end of each trace at a frequency a little above the respective resonance. The baselines are somewhat skewed by the presence of other resonances in this vicinity (some caused by reflections external to the inner shell), but it is felt this is tolerable in this case. This same effect also causes a change in the apparent shape of the $TM_{4,1,0}$ mode resonance which is rather close to the $TM_{2,6,N}$ and $TM_{1,10,N}$ modes that in turn are somewhat split up as a result of asymmetries. There is also some lowering of the Q when the device is operating (as a result of the electron collisions). This is probably the principal effect that causes the TE mode peak to be lower with the high voltage on--even after allowance is made for simple skewing of the baseline.³

A. 17.5 ma to the Inner Sphere

B. 15 ma to the Inner Sphere

Fig. 4. Frequency Shifts at Turn-Off of the High Voltage.

Microwave transmission as a function of frequency.

Operating potential: 20 kV

Ion Gauge Reading: 2.5 Microns (Deuterium)

II. THE CIRCUITS

In order to switch the high voltage on and off at the desired rate and also monitor small frequency shifts in a "continuous" manner, it was necessary to develop circuitry to control and perform these operations.

The High-Voltage Switch

To establish the "plasma" and "no plasma" conditions for the continuous recording of frequency shifts, it was necessary to develop a method of switching the ion current injected into the sphere on and off quickly and without excessive jitter. It was decided to switch the high voltage applied to the sphere, although it would have been possible to switch the ion beams from the guns. The latter method would have entailed switching of the six guns and would have complicated the ion gun adjustments. For the present tests it was thought desirable to be able to operate at voltages up to 50 kv (the power supply capability), although operation even up to 20 kv would be meaningful. To switch the high voltage it was considered worthwhile to attempt the use of a Jennings high-voltage vacuum switch (Fig. 5) (interrupter model R1, using tungsten electrodes, driven by a vacuum interrupter actuating mechanism model 4002) which was available. This is a solenoid-activated, single pole, single throw, normally-closed switch. Bench tests of the

Fig. 5. Jennings High Voltage Vacuum Switch
(with Silicone Dielectric Coating)

Fig. 6. The Vacuum Switch in Position on the Device.

switch (made with less current than would be used in actual operation of the device) showed that although the switch itself would apparently operate properly at 50 kV, arcing to the actuator mechanism occurred at about 25 kV. To increase the breakdown limit, the insulators were coated with General Electric Silicone Seal. Upon retesting up to 40 kV the insulation was found to hold.

To control the solenoid actuator and allow it to open and close the high-voltage contacts cleanly and regularly, a triac gating circuit is used (Fig. 8). The triac is controlled by a 5-volt (positive) square wave of the frequency at which the high-voltage switch is to be switched (Fig. 9). The triac circuit was found to control the solenoid in the desired manner, but on the closing of the high-voltage contacts, a bouncing occurs which produces a raggedness of the high voltage applied to the device (Fig. 9). As the switching rate of the high voltage switch is increased, the portion of the signal containing "bounce" of course increases relative to the "clean" portion of the signal. This condition provided an upper limit of about 10 Hz on the rate at which the high-voltage switch could be driven while still providing a clean portion of each half period for sampling the resonant frequencies. (After several months of operation, it was found that at 10 Hz, the lag in the closing of the switch and the bounce of the contacts, made the high voltage to the sphere very noisy (Fig. 10). Since the absolute lag and bounce are not a function of the rate of switching, the use of a slower switching rate

Fig. 7. Triac Circuit Mounted on Base Plate

Fig. 8. Triac Circuit Diagram

MASTER SAWTOOTH
(Line Synchronized)

SQUARE WAVE
(For Driving Triac Circuit
in the High Voltage Switch)

HIGH VOLTAGE
(Applied to the Device)

Fig. 9. High Voltage Switch Waveforms.

reduces the unuseable portion of the signal relative to the total viewing time (Fig. 11). A 5 Hz switching rate was then decided upon because of the ease in making the change in the detection instrumentation. The cause of the deterioration of the switch operation is not known although a possible cause is the weakening of the spring which returns the contacts of the switch to their normally closed state.)

The microwave signal generator to be used shows a small amount of residual frequency modulation (50 kHz) synchronized with the power line frequency. For this reason it is important that the repeated sampling of the microwave resonance be performed always at approximately the same phase of the line voltage. The actuator for the switch is rated for ac operation, but the manufacturer advised that dc operation, with a suitably shaped voltage signal, would give optimum performance and maximum lifetime of the actuator solenoid.⁴ However, in view of the desirability of synchronizing the switching with the line voltage (to nullify the effect of the residual microwave frequency modulation), the use of an ac drive to the actuator was considered permissible. When the initial and final phase are properly selected, the jitter is approximately that of the ideal dc operation. Although no dc tests were performed, ac tests showed that the jitter could be minimized to a useable level. In order to prolong the life of the actuator, a variable resistor, in series with the actuator coil and the triac, is used to lower the voltage to the minimum value that still gives reliable switching. Originally a triac with a blocking

Fig. 10. High Voltage Waveform Switched at 10 Hz. (25 kV and 2.5 mA, Ten Sweeps).

Fig. 11. High Voltage Waveform Switched at 5 Hz. (17 kV and 1.5 mA, Ten Sweeps).

voltage of 200 V was used and during long periods of operation of the device, when the high-voltage switch was used longer than about thirty minutes, occasional "misfires" (spurious switch operations) occurred. After the installation of a triac with a higher blocking voltage (400 V), "misfires" have not been observed. The precise cause of this difficulty has not yet been determined although deterioration of the triac characteristics and increase of actuator coil resistance with increased operating temperature are likely factors.

From bench tests of the high-voltage switch it was determined that a useable high-voltage signal (giving 1/60 second of "clean" microwave sweep time for each state) could be obtained with a driving square wave frequency of 10 Hz or less (Fig. 13). Because of the bounce on closing, the possibility of using an asymmetric square wave to control the switch was considered, with the asymmetry adjustable to give maximum useable time for "viewing" the cavity with the microwaves. The idea of using the asymmetric square wave was abandoned, however, in order to facilitate the development of the needed switching waveforms. Synchronization with the 60 Hz line suggested that a 10 Hz square wave would be the most convenient to work with, although square waves of less than 10 Hz could be used. This made it convenient to use a third of each on-off portion of the high-voltage signal for sampling the resonant frequencies. With the microwaves being swept at line frequency and the high voltage being switched at 10 Hz, it is compatible to look at

Fig. 12. High Voltage Waveform on the Closing of the High Voltage Switch (with Current)

Fig. 13. High Voltage Waveform Applied to the Device (No Current, Single Trace).

only each third microwave sweep.

The triac circuit was mounted (Fig. 7, page 13) on the high-voltage switch and the switch shock-mounted to a metal plate. During testing under high voltage it was determined to be necessary to improve the shielding of the triac circuit. A copper braid was initially used to bypass the insulation of the shock mount and ground the box shielding the triac circuit but metal foil was finally used to further reduce the inductance.

The Measurement Circuitry

In order to measure frequency shifts, use is made of the direct correspondence of sweep voltage and frequency in most swept signal generators. A signal voltage proportional to the frequency shift is developed by sampling the sweep voltage at resonance. During the "on" state of the device (i.e., with plasma present) a positive voltage gate is generated, starting when the resonant frequency is reached, and similarly during the "off" state (no plasma) of the device. The voltage level of the sweep voltage is sampled at these two times, and the difference in the voltage level from the two sample-hold circuits (representing the difference in the "on" and "off" states) is then utilized to give an output signal proportional to the frequency shift.

To perform the various operations needed, i.e., to cycle the high-voltage switch at 10 Hz, to look at only the third sweep of the microwave for sensing the resonant

frequency and to compare alternate third sweeps for determining the shift of the microwave resonance, it was necessary to develop various waveforms. Upon investigation of these control waveforms, it was considered that TTL (transistor-transistor logic) circuitry would be suitable for producing them.

In order to measure the frequency shift of the resonance modes it is necessary to sense the resonance peak of each mode separately. This is accomplished by the development of line-synchronized, digital waveforms which control the internal gate and trigger circuits of a Hewlett-Packard 180A oscilloscope. During each third sweep, a positive gate is developed by a negative gate triggered by the oscilloscope, at resonance. Since the gate is triggered at resonance, it will be initiated at different phases of the master sawtooth, depending on whether the device is in the "on" or "off" state. By sampling the sweep voltage during the on part of the gate and holding that voltage, different voltage levels (which are proportional to the frequency shift) are obtained.

A block diagram of the overall measurement circuit is given in Fig. 14. Most of the units are commercially available instruments or components whose functions are apparent. The "Timing and Measurement Circuits," however, are designed for this particular measurement and their operation will be discussed in terms of the various waveforms associated with them. An expanded block diagram of the

Fig. 14. Block Diagram of the Circuit for Detection and Continuous Recording of Frequency Shifts of Two Microwave Cavity Resonances.

timing and measurement circuits is given in Fig. 15 and detailed circuit diagrams of the units in this figure are given in Appendix A.

To develop the desired output waveforms several intermediate steps are required and a representation of the timing sequence for all the waveforms associated with the measurement of one mode is shown in Fig. 16. The sawtooth sweep voltage from a master line-synchronized oscilloscope (top waveform in Fig. 16) is fed into a clock circuit which produces 60 Hz, 5-volt pulses. These clock pulses are then used to switch a logic circuit which produces the three waveforms Q_0 , Q_1 , and Q_2 (Fig. 16); $\bar{Q}_2$ ("not Q_2 ") being the square wave used to drive the high-voltage switch activation circuit (actually waveform Q_2 itself would also be appropriate for this purpose). Q_0 and Q_1 are combined with Q_2 in the "measurement window" circuit to give a gate during each microwave sweep for which a sensing of the resonance is desired.

The signal from the microwave detector (transmission resonance peak shown as the ninth wave in Fig. 16) is amplified and differentiated with a Tektronix Type "O" operational amplifier plug-in unit. The differentiated resonance signal, which passes through zero voltage at the peak of the resonance, is used to trigger a gate in the H.P. oscilloscope. Because of the noise on the signal from the detector, a low-pass RC filter is sometimes used either before or after the differentiator. The delayed gate from the H.P. oscilloscope, when combined with the measurement window signal (in an "and"

Fig. 15. The Timing and Measurement Circuits Portion of Fig. 14.

Fig. 16. Waveforms Used for the Detection and Continuous Recording of the Frequency Shift of a Single Microwave Cavity Resonance.

gate circuit), gives a gate of the same frequency as that of the measurement window. Thus the measurement window eliminates two of each three of the gates, and the remaining gates correspond to those shown as the twelfth waveform in Fig. 16, where it is designated as the "Negative Gate Combined with Measurement Window." This gate is taken into a sample-and-hold amplifier which samples the sweep voltage while the gate is on (when resonance occurs), and then holds at that voltage level until the next gate, producing the thirteenth waveform of Fig. 16. This output is taken into a second sample-and-hold amplifier and also into a difference amplifier. The second sample-and-hold samples the output of the first sample-and-hold during the time the device is in the "on" state and the measurement window is in the "off" state (fourteenth waveform of Fig. 16). The output of this second sample-and-hold is taken into the difference amplifier with the output of the first sample-and-hold and the difference of the two signals is determined (waveform 15 of Fig. 16). Because the difference of the outputs of the first and second sample-and-holds is taken into the difference amplifier, the sample-to-hold offset of the second sample-and-hold can cause an inaccurate difference. The offset of the first sample-and-hold does not come into account since this offset, which goes into the second sample-and-hold, is subtracted out at the difference amplifier. In order to eliminate the offset of the second sample-and-hold, it is possible (although at this time it has not been done) to introduce a compensating offset voltage.

This would then allow for a complete nulling of the sample-to-hold offset. For a portion of each switching period this difference signal is proportional to the frequency shift of the resonance peak being measured. This signal can be taken directly into a recorder to give useful information. In order to get additional information about the electron density within the cavity, two resonance peaks can be viewed "simultaneously," using the method described above, and a ratio of the outputs of the two difference amplifiers is found using an integrated circuit ratio detector. This output ratio, which may contain useful information about the spatial distribution of the electron density (waveform 13, Fig. 17), is taken into another sample-hold amplifier which samples the ratio signal when the device is in the "off" state and the measurement window is also off in order to eliminate the portion of the ratio when the output of mode I is zero (waveform 14 of Fig. 16). This output is then continuously recorded on a Sanborn 350 Six Channel Recorder.

Calibration

With no high voltage applied to the hollow sphere within the device, the resonance pattern is always that of the empty spherical cavity. In this case there is no frequency shift and hence the negative gate pulse (the oscilloscope "delayed gate") that is initiated at resonance (the eleventh waveform of Fig. 16) normally occurs always

Fig. 17. Detection and Recording Waveforms for Two Resonance Modes.

at the same position with respect to the master sawtooth for both the positive and zero state of the square wave. The output voltage levels from the sample-and-hold amplifiers are thus constant, and the difference in signal output represents the zero frequency shift level. When the electrons are present during the "on" state of the device, the resonance will appear at different phases of the sweep voltage for the two states of the square wave. This in turn makes the "on" portion of the sample-and-hold output voltage higher than the "off" portion (or vice versa if the frequency is swept down rather than up), resulting in a recorder deflection which is proportional to the frequency shift caused by the presence of the electrons.

To determine the relation of the recorder deflection to the frequency shift, a calibration circuit was developed. This adds a small voltage from the square wave of the logic circuit to the master voltage sweep (derived from a line-synchronized oscilloscope) and uses the resulting wave to frequency-modulate the microwave generator. The frequency modulation waveform (shown as the seventh waveform in Fig. 16) has a square-wave component to illustrate this calibration method. The square wave is first taken through a variable attenuator so that the amount to be combined with the sweep can be varied. By adjusting the attenuation of the square wave, an artificial "shift" of desired magnitude can be produced with the circuit. This shift can be calibrated in terms of a frequency shift of the microwave resonance by measuring this artificial horizontal shift of

a resonance peak on the oscilloscope screen (while viewing the detector output) and then directly calibrating the oscilloscope screen. This calibration is accomplished by finding a broad peak in the detector output and marking a frequency difference with a wavemeter in the microwave line. The oscilloscope delayed gate (with the delayed sweep on "auto") is adjusted so that its length corresponds to the frequency change indicated by the wavemeter. This same procedure is used to calibrate both H.P. oscilloscopes (which may be associated with different microwave signal generators). The calibrator circuit is then used to introduce an artificial frequency shift which can be measured by the calibrated oscilloscopes. The recorder output is then calibrated from this known "frequency shift."

Sensitivity Considerations

Initially the detection circuit was set up to look at only one resonance at a time and hence the shift of one mode. In viewing a second mode, an additional sweep generator, oscilloscope (with built-in delayed sweep circuits), and recorder channel are used. It is possible with the sacrifice of flexibility and sensitivity, to view both modes using a single sweep generator if the modes are not too widely separated.

The initial measurements did not use the sample-hold modules, but instead were made with a detection circuit (described in Appendix B) that produced positive and negative gates of different widths such that the difference was

proportional to the frequency shift. These gate signals were then filtered using a low-pass RC filter to give an off-set voltage proportional to the shift in the resonance peak. The long filtering time constant imposed a severe restriction on the overall response time of the circuit. Furthermore occasional malfunctioning of the switching circuit could cause exceptionally large signals that would saturate the filter for long periods. The sample-and-hold technique, which is discussed in this thesis, does not filter the output and therefore if misfires do occur the detection circuit can recover in one period.

Testing of the detection circuit while operating the device indicated a necessity for improved sensitivity in detecting a frequency shift. These initial tests were made using a single Hewlett-Packard H01-694A Microwave Sweep Generator to sweep through both modes of interest. The time necessary for a single signal source to sweep between the two resonance modes of interest is usually long in comparison with the time necessary to sweep through either of the resonance modes. This wasted time in sweeping between the modes ultimately results in a reduction of the sensitivity, since time is lost that could otherwise be used for filtering the noise in the detected microwave signal or for averaging the results of repeated sweeps through each resonance. This problem is overcome through the use of two sweep generators, one for each resonance mode being viewed. This allows for a slower sweep, making it possible to filter out noise of lower frequency. The slower rate makes the absolute jitter times

a smaller percentage of the output signal. In order to sweep at a slower rate and view both modes, the two sweep generators, with their sweep selector set on continuous wave, are each swept through their specific resonance of interest by means of the same sawtooth wave into the external frequency modulation (Ex FM) circuit. To view both resonance modes during each sweep, a blanking 60 Hz square wave is fed into the external amplitude modulation (Ex AM) circuit of each sweep generator. A single Hewlett-Packard 211A Square Wave Generator is used to produce the two square waves which differ in phase by 180° . This method enables one mode to be viewed during the first half of the sweep and the second mode during the second half, with the same detector for both modes. The time sequence of various waveforms for the two-mode measurement is given in Fig. 17. By reducing the wasted time between the modes, the difference in the voltage levels between the "on" and the "off" states of the output wave, indicating a frequency shift of the resonance peak, can be adjusted to give maximum sensitivity.

Fig. 18. An Example of Data Taken with the Measurement Circuit.

III. PERFORMANCE OF THE CIRCUIT

The device was put into operation to test the switching and the electronic detection circuits under actual operating conditions. The device was operated using deuterium at various pressures and varying the high voltage between 0 and 40 kV. Both the high-voltage switch and the digital circuitry performed as expected showing a definite frequency shift when the high voltage was applied to the inner sphere of the device and the deuterium pressure inside the device was above 1.0×10^{-3} mm-Hg. During operation of the switch, a puncture (electrical breakdown) occurred in the dielectric coating of the vacuum switch. The switch was recoated and successful high voltage operation (to 40 kV) was resumed even prior to the curing of the dielectric.

In subsequent research on the confinement device, some measurements were made in which the ratio of the frequency shifts of the two modes was continuously recorded as operating parameters were varied. The operating parameters are inter-related, however, and sometimes difficult to control and the most meaningful tests have involved a series of three-second recordings, with each run being taken under constant operating conditions. After each run the system is readjusted to effect a change in a single parameter.

Some of the experimental data is shown in Fig. 18 which gives a plot of the measured frequency shifts of two

modes as a function of the background pressure inside the device. The error bars shown on the plots at the left indicate the statistical fluctuation in the recorded signal. This in turn depends on the behavior of the device itself in addition to the behavior of the measurement circuit.

The upper plot, which utilized a resonance with a higher Q , shows a threshold sensitivity for the measurement of Δf of the order of 20 KHz at an operating frequency of 10.479 GHz. (This allowed electron densities of the order of $10^7/\text{cm}^3$ to be observed.) Thus the measurement circuit itself is capable of a threshold sensitivity of the order of two parts in 10^6 or better.

Recommendations

To output the data in a digital form, which could be analyzed quicker and easier, an analog to digital converter could be used with a digital printer instead of the recorder. The sample-hold technique lends itself readily to this approach since the sample-hold circuits put out a fairly constant voltage while in the "hold" position.

The dc offset on the second sample-hold circuit can become critical when the ratio of the two modes is being measured. To eliminate this dc, a nulling circuit could be incorporated following the second sample-hold. The process would require a fair amount of additional circuitry which the experiment was not felt to justify at this time.

IV. SUMMARY

This thesis describes the development of instrumentation for continuously recording the frequency shift of selected spherical cavity resonances produced by the presence of a plasma. This problem relates specifically to the study of charged-particle distribution in an inertial electrostatic confinement device being conducted at Brigham Young University.

The instrumentation includes an electronic circuit for switching a high-voltage-vacuum switch, digital timing circuits, integrated circuit sample-and-hold and ratio amplifiers, and other circuitry for the continuous recording of the frequency shifts of two microwave cavity resonances and their ratio.

Although the circuits were tested and the performance of the circuits are described in this thesis, the operation of the inertial electrostatic confinement device itself is not discussed.

The circuitry employed for the high-voltage switch is a triac-controlled circuit which drives the high-voltage switch actuator mechanism at a sub-multiple of the line frequency. Although this mechanical switch has (by electronic standards) appreciable jitter and upon closure has interruptions due to bouncing of the contacts, there is enough useable time each period to accomplish the desired

purpose at a switching rate of 5 Hz.

The digital circuitry designed for the continuous recording of frequency shifts develops several voltage waveforms which both control and sense changes in the voltage output of the microwave signal from the device, resulting in an indication of the shifts in the resonant frequencies. The primary components of this circuitry are a TTL circuit which develops a square wave, and a measurement window, a sample-and-hold circuit which samples the sweep voltage during resonance, and a ratio circuit for giving a ratio of the two resonance mode. The remaining portions of the circuitry provide the additional waveforms for detection of resonance shifts. These additional circuits are principally contained in the circuitry of commercial units such as the Hewlett-Packard 180 A oscilloscope and the Hewlett-Packard H01-694A Microwave Sweep Generator.

Tests of the system in actual operation showed that it was possible to detect frequency shifts of the order of two parts in 10^6 .

LIST OF REFERENCES

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3. A. L. Gardner, G. A. Meeks, A. I. Y. Chan, and K. W. Struve, "Study of Charged-Particle Distribution in an Electrostatic Confinement System" (unpublished progress report No. COO-2180-1 prepared for the U.S. Atomic Energy Commission under contract No. AT (11-1)-2180) (1972)
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APPENDIXES

APPENDIX A

ELECTRONIC CIRCUITRY

In Figures 19a through 19c detailed drawings of the digital circuits are given. The block diagram in Figure 15 shows how these various circuits fit together.

The electronic components were mounted on two circuit boards which were rack-mounted near the recorder.

LIST OF SYMBOLS AND COMPONENTS in Circuit Diagrams

Pin connections from board to board or from a board to an external component
Intra-board connections (like numbers connect)
BNC female output jack
Integrated circuit NAND gate	7400
Integrated circuit AND gate	7408
Integrated circuit J-K Flip-Flop	74107
Integrated circuit Inverter	7406
Integrated circuit Operational Amplifier (Motorola HEP C6052P)	6052
Integrated circuit Operational Amplifier (Analog Devices AD504J)	AD504J
Integrated circuit Five Volt Regulator	LM309
NPN Transistor	2N4400
Sample-Hold Amplifier (Hybrid Systems Corp 725LH)	SHA 725LH
Ratio Amplifier (Analog Devices AD5235D)	AD5235D

MEASUREMENT WINDOW
CIRCUIT

CALIBRATION CIRCUIT

Fig. 19a. Detailed Drawings of Circuits Shown in Fig. 15.

LOGIC CIRCUIT

FIVE VOLT REGULATOR
CIRCUIT

CLOCK CIRCUIT

Fig. 19b. Detailed Drawings of Circuits Shown in Fig. 15.

APPENDIX B

THE INITIAL METHOD OF MEASUREMENT

Initially circuitry was designed and built to measure the frequency shift of the resonance modes by using the direct correspondence of time and frequency in a recurrently swept signal generator. A signal voltage proportional to the frequency shift was developed by averaging the signal from voltage gates of opposite sign.

During the "on" state of the device a positive voltage gate was generated (starting at a fixed point in the sweep) that ended when the resonant frequency was reached. Similarly during the "off" state of the device a negative voltage gate was developed. The difference in the gate lengths is thus proportional to the frequency shift between the "on" and "off" states. After one complete "on-off" cycle the integrated voltage from the sum of the two gates is proportional to the frequency shift (Fig. 20).

The circuitry to perform the needed operations is based on the same logic circuitry that is described in the body of this thesis. The difference is in the parts of the circuit described as the frequency shift wave clock, the frequency shift wave, and the output wave (Fig. 22). These three voltage waveforms were produced from the logic output combined with the gate pulses produced by the oscilloscope

Fig. 20. Waveforms Used for the Detection and Continuous Recording of Frequency Shifts of Two Microwave Cavity Resonances Using the Initial Method.

Fig. 21. Block Diagram of the Circuits for Detection and Continuous Recording of Two Microwave Cavity Resonances Using the Initial Method.

Fig. 22. The Block Diagram of the Logic Portion of Fig. 20.

MASTER SAWTOOTH (Sweeps both Microwave
Generators)

SQUARE WAVE

MEASUREMENT WINDOW

MICROWAVE SIGNAL (Using Two Signal Generators
Alternately Blanked)

HEWLETT-PACKARD 180A MAIN SWEEP

DELAYED TRIGGER FROM H. P. 180A OSCILLOSCOPE

DELAYED GATE TRIGGERED AT RESONANCE

OUTPUT WAVE I

HEWLETT-PACKARD 181A MAIN SWEEP

DELAYED TRIGGER FROM H. P. 181A OSCILLOSCOPE

DELAYED GATE TRIGGERED AT RESONANCE

OUTPUT WAVE II

Fig. 23. Waveforms for Detection of Frequency Shifts of Two Resonance
Modes Using the Initial Method.

Fig. 24. The Two Output Waves Superimposed (10511 MHz and 10547 MHz) and Resonant Peaks.

Fig. 25. The Two Output Waves Superimposed (with Frequency Shift).

OUTPUT WAVE
CIRCUIT

FREQUENCY SHIFT WAVE
CLOCK CIRCUIT

FREQUENCY SHIFT WAVE
DIGITAL CIRCUIT

Fig. 26. Detailed Drawings of Circuits for Initial Method.

when resonance was reached. The output wave for each mode (which contains the frequency shift information) is filtered and the ratio of output voltages for two modes taken using an integrated circuit ratio detector.