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Scientific Report No. 341

PLASMA OSCILLATIONS IN A SPHERICAL, MAGNETIZED, COLD CATHODE DISCHARGE

by

P. E. Schmidt and R. G. Quinn

October 20, 1969

IONOSPHERE RESEARCH LABORATORY

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Ionosphere Research Laboratory

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ABSTRACT

Plasma oscillations of very low frequency (0 - 30 kHz) have been found in a cold cathode DC discharge, where the cathode consists of an uniformly magnetized sphere. Under certain pressure and discharge conditions the plasma becomes trapped in the magnetic dipole field of the cathode. Under these conditions plasma oscillations occur. The plasma oscillations have been studied in detail with respect to the two terminal characteristic of the device. It is found that the frequency of the plasma fluctuations decreases with increasing current, gas pressure, ion mass, and decreasing voltage. No dependence of the frequency on the external series resistance or magnetic field is noticeable. The oscillations are rich in harmonics. In addition to the fundamental, the 2nd and 3rd harmonic have been studied. Experimentally it is found that $f = A\,R_{DC}$, where f is the frequency, A a constant dependent upon pressure and R_{DC} is the ratio of the DC voltage between the electrodes and the DC discharge current.

It is also shown that the phenomena could serve as the basis for a highly sensitive pressure gauge.

1. INTRODUCTION

The laboratory plasmas generated by a DC discharge are normally typified by specifying the operating pressure and the type of cathode. With respect to pressure one distinguishes between low pressure discharges ($p < 0.01$ Torr) and high pressure discharges ($p > 0.1$ Torr). For the cathodes, one makes use of the distinction between hot cathodes and cold cathodes.

Most of the experimental research which has been done deals with hot cathode plasma devices. Crawford (1961), in a review paper of plasma oscillations in a low pressure DC discharge gives an extensive bibliography of these investigations. Oscillations found in thermally generated plasmas in conjunction with thermionic emission from a hot cathode have been described by D'Angelo and Motley (1963). Appleton and West (1923) observed ionic oscillations in a cold cathode discharge without magnetic field at a pressure of 0.25 Torr in the frequency range 1 to 100 kHz. There has been a recently revived interest in cold cathode discharges for use in lasers, where hollow cold cathodes are used. (Hochuli et. al. 1965 and 1967).

The plasma device under study in this paper uses a spherical cold cathode made of Alnico alloys and operates at a pressure of approximately 0.5 up to 8 Torr depending upon the type of residual gas. It is found that, under certain discharge conditions, plasma oscillations occur in the VLF and LF range.

This paper reports the results of the research effort which was directed toward the determination of the effect of the DC discharge voltage, the DC discharge current, the pressure, the external series resistance, the magnetic field, the ion species and the diameter of the cathode on the frequency, magnitude and harmonic content of the detected oscillations.

At the present time, it is not clear what type of plasma oscillations are occurring. Hopefully additional insight into the phenomena will be gained by a new series of experiments now underway and devised to investigate the influence of the above mentioned effects upon the wavelength of the oscillations.

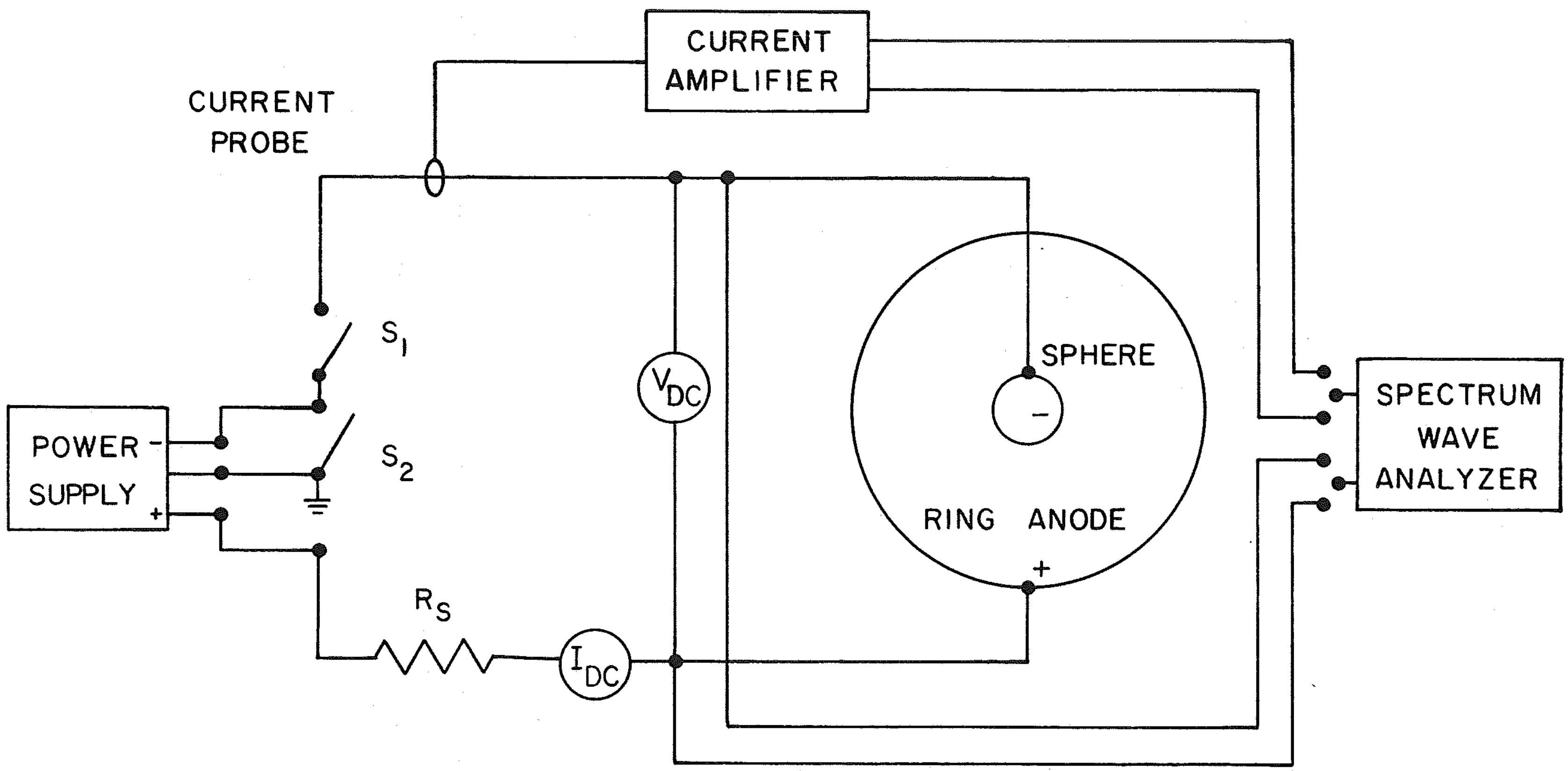
2. APPARATUS AND MEASURING PROCEDURE

2.1 Description of the Apparatus

The schematic of the experimental apparatus is presented in figure 2.1. A sphere is placed upon a copper rod which also serves as a conductor in addition to a support. Various spheres were used. Table 2.1 enumerates them by specifying respectively the material and the diameter. The last column refers to the curves labelled in figure 2.2. The latter have been obtained by means of a Bell, model 620, gaussmeter. The rod is placed in a solid tripod stand which is aligned along the axis of a cylindrical vacuum chamber. The sphere is used as a cold cathode in a DC discharge. The anode is a ring of copper wire fixed at the innerwall of the vacuum chamber and located in the equatorial plane of the magnetic dipole. The position and distance of the anode with respect to the cathode is not critical (Quinn et. al. 1966).

The vacuum chamber used in the experiment is a glass bell jar on a stainless steel base plate. The pumping unit is a Veeco VS 400 consisting of a roughing and a diffusion pump.

The type of the plasma obtained with the above described electrode geometry has been investigated previously by Quinn et. al. (1965, 1966) and Twardeck (1968). The plasma is generated by applying a DC voltage across the electrodes in vacuum. A plasma belt is formed in the equatorial plane under certain pressure and discharge conditions.



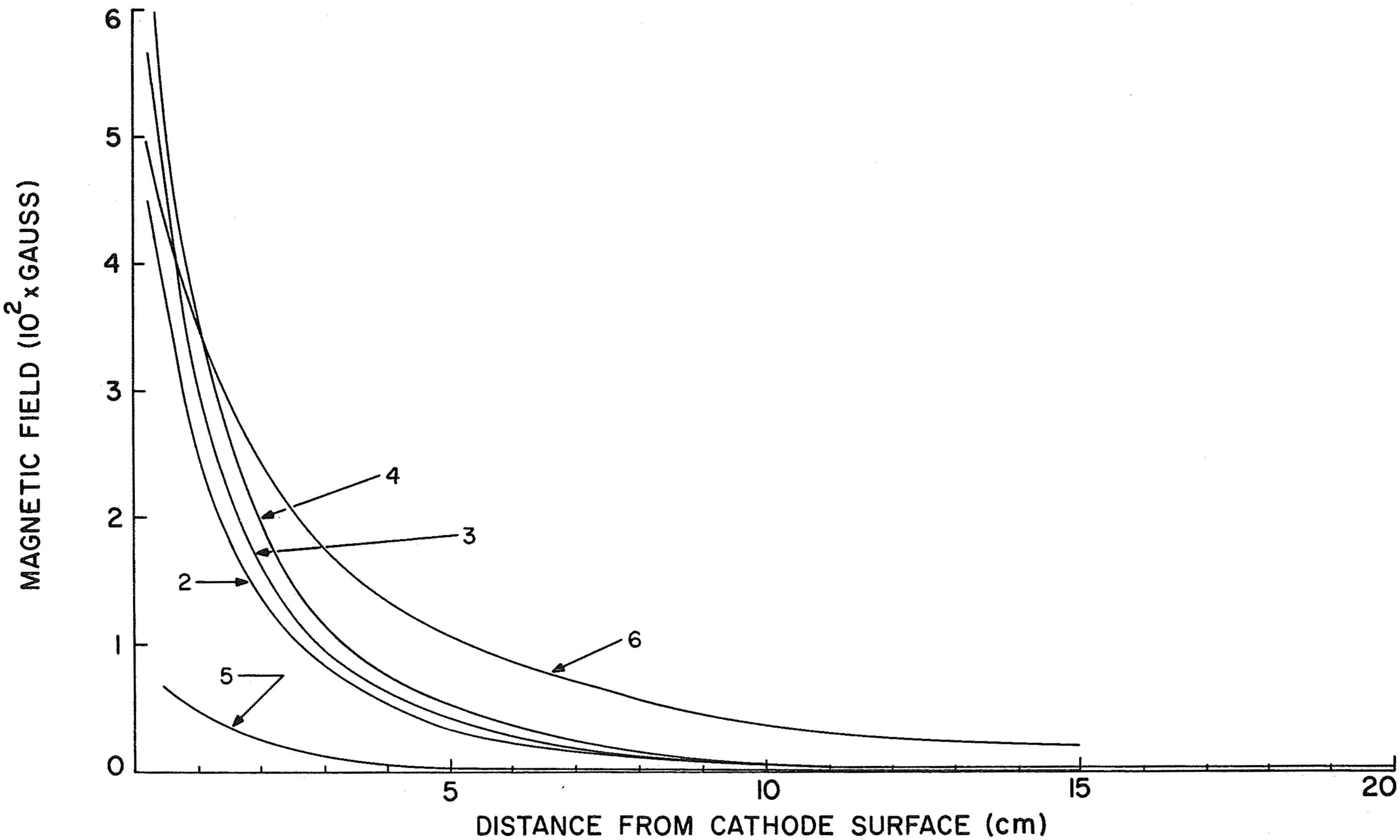
Schematic of the Experimental Apparatus

FIGURE 2.1

TABLE 2. 1

Specifications of the Spherical Cathodes

Number Designation	Material	Diameter (cm)	Magnetic Field
1	ALNICO 5	6. 4	Unmagnetized
2	ALNICO 5	6. 4	curve 2
3	ALNICO 6	6. 4	curve 3
4	ALNICO 7	6. 4	curve 4
5	ALNICO 5	3. 3	curve 5
6	ALNICO 5	15. 4	curve 6



Magnetic Field Strength in Equatorial Plane vs Distance

FIGURE 2.2

2.2 Measurement Procedures

The vacuum chamber is filled with a particular gas to a selected pressure. With switch S_1 (figure 2.1) closed and S_2 open, the DC biasing voltage is increased until the gas breaks down and the plasma is confined to the equatorial plane of the magnetized sphere. Next, switch S_2 is closed connecting the cathode to ground potential. The reason for this specific order in the starting precedure is to avoid discharges from the anode toward the sphere tripod stand and/or the baseplate.

The plasma trapped in the magnetic dipolar field has a dense ring region (negative glow) near the surface of the cathode. A VLF plasma oscillation is detected when the plasma forms.

The frequency of the plasma oscillations can be changed by varying the pressure or the DC power supply. The generated plasma oscillations occur in the VLF (0 to 30 kHz) range and the LF (30 to 300 kHz) range and can be detected by different methods:

A. A wire antenna wound around the outside of the belljar.

B. Detected directly across the electrode gap as shown in figure 2.1. As an alternative, the oscillations can also be detected using an hp 1110A current probe with hp 1111A current amplifier.

C. Detected by means of an exposed wire probe in the plasma.

Each detection device can be connected to a suitable spectrum wave analyzer. The one used consisted of a Tektronix Type 544 Oscilloscope, plug-in unit type 1L-5 and a P6008 attenuator probe.

Using a Type M multitrace plug-in unit with the Type 544 Tektronix oscilloscope, it was observed that the four pick up devices, i.e. antenna, voltage probe, current probe and immersed wire probe give the same periodic wave form but have different amplitudes.

The amplitude of the oscillations picked up by means of the wire antenna is dependent upon the number of turns. The ratio of the ac voltage to the ac current, detected by means of the voltage and current probe, is equal to the serie resistance (R_s).

This paper deals exclusively with the VLF detected by using the voltage probe together with the spectrum wave analyzer.

The plasma device is considered as a two terminal black box. The quantities measured are: pressure; DC voltage, defined as the voltage over the electrode gap; DC current, defined as the current between the electrode gap; frequency and magnitude of the fundamental, 2nd and 3rd harmonic (rms Volt) of the plasma fluctuations.

3. EXPERIMENTAL RESULTS

3.1 Two Terminal Characteristic with Constant Pressure

All data given in the next section are obtained keeping the pressure fixed while changing the DC discharge conditions.

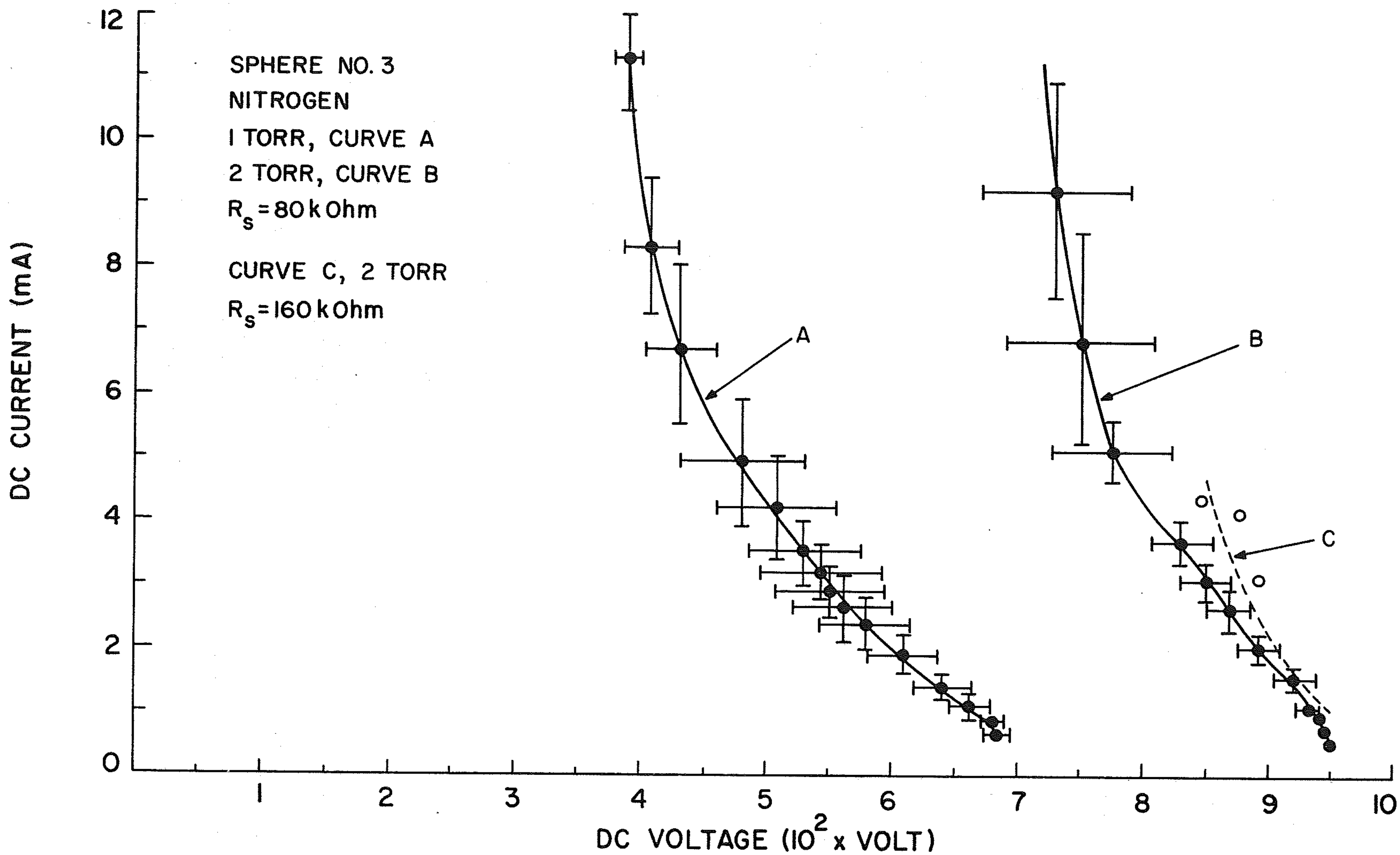
3.1.1 General Considerations

The following results were obtained using the set-up as shown in figure 2.1. The nitrogen gas is broken down and a plasma belt is formed in the equatorial plane of the sphere no. 3 at a pressure of 2 torr.

The discharge characteristic under above conditions is presented in figure 3.1 (curve B). It is noticed that at the high current and low voltage side large error bars are needed. The reason is that it is difficult to maintain the same pressure and cathode surface conditions. Apparently, at the high voltage and low current side these effects have a smaller contribution.

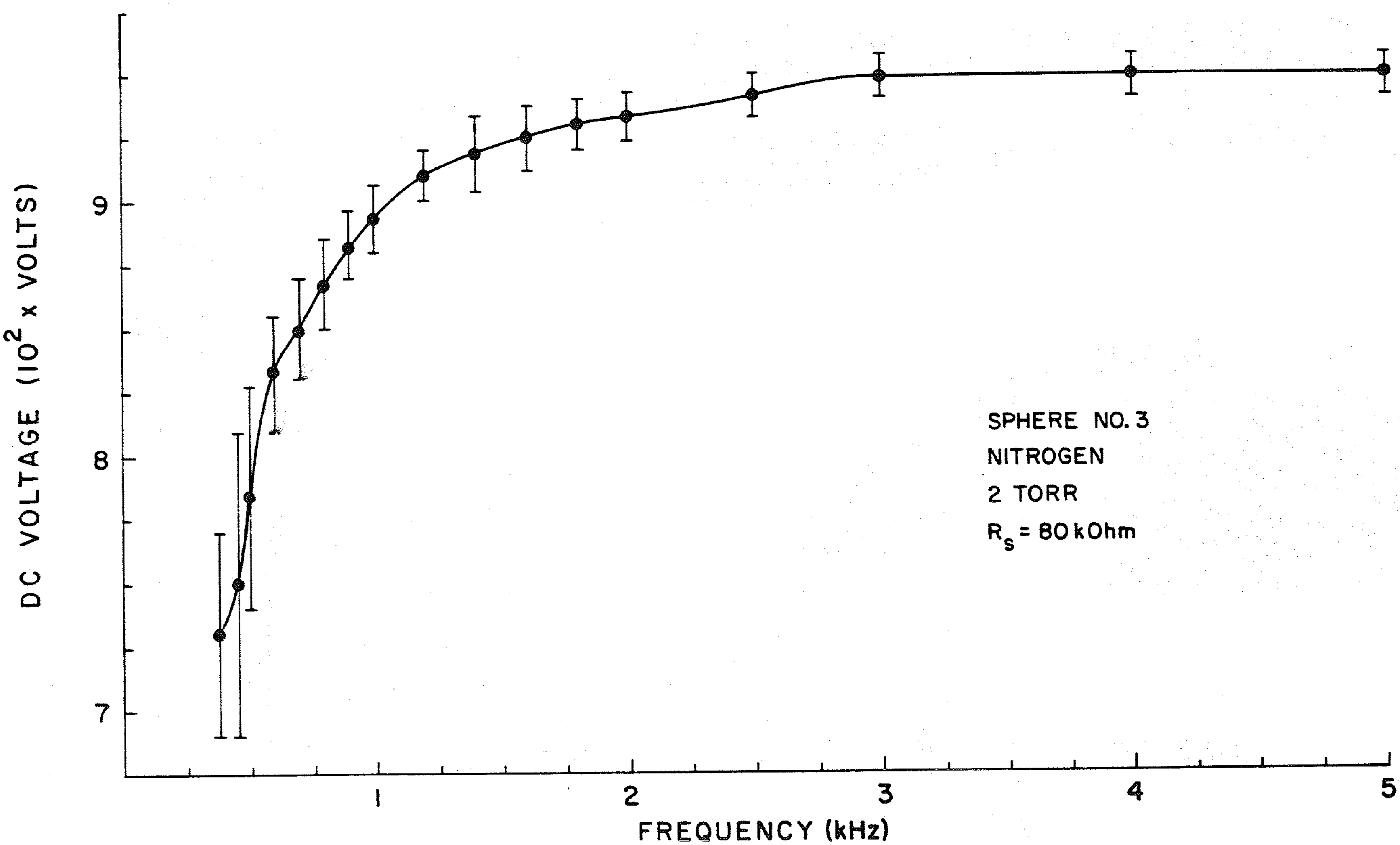
In figures 3.2 and 3.3, DC voltage and DC current are plotted versus frequency. It is interesting to notice that the lowest frequency occurs for high DC current and low DC voltage while the highest frequency is obtained for low DC current and high DC voltage.

The figures 3.4, 3.5 and 3.6 represent respectively the magnitude of the fundamental, the 2nd harmonic and the 3rd harmonic in rms volt versus frequency. It is noticed that the fundamental has two clearly distinguishable minima and maxima. The 2nd harmonic also has two maxima, although the 1st maximum is suppressed, but only one minimum. The 3rd harmonic has only one distinguishable



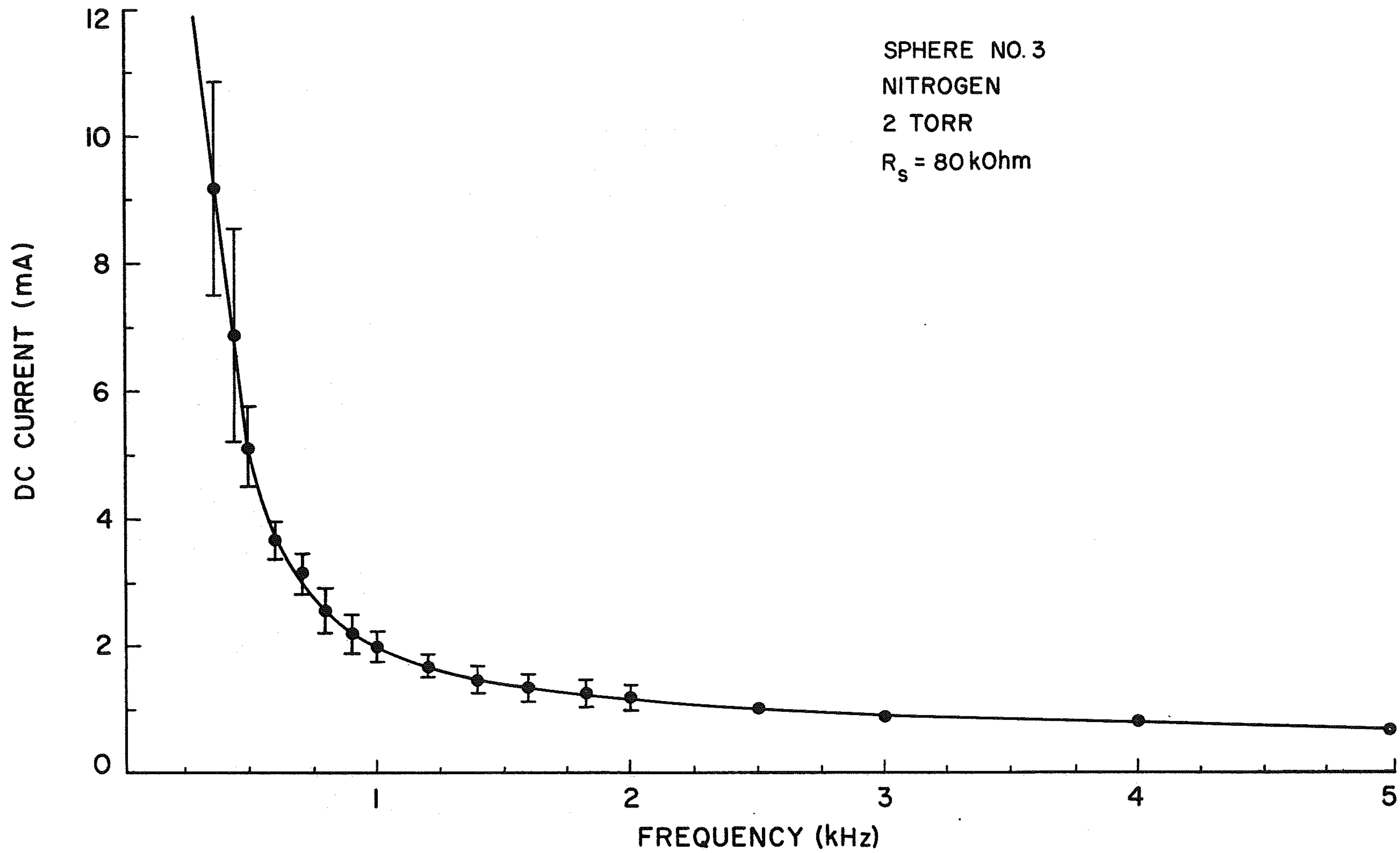
DC Discharge Characteristic

FIGURE 3.1



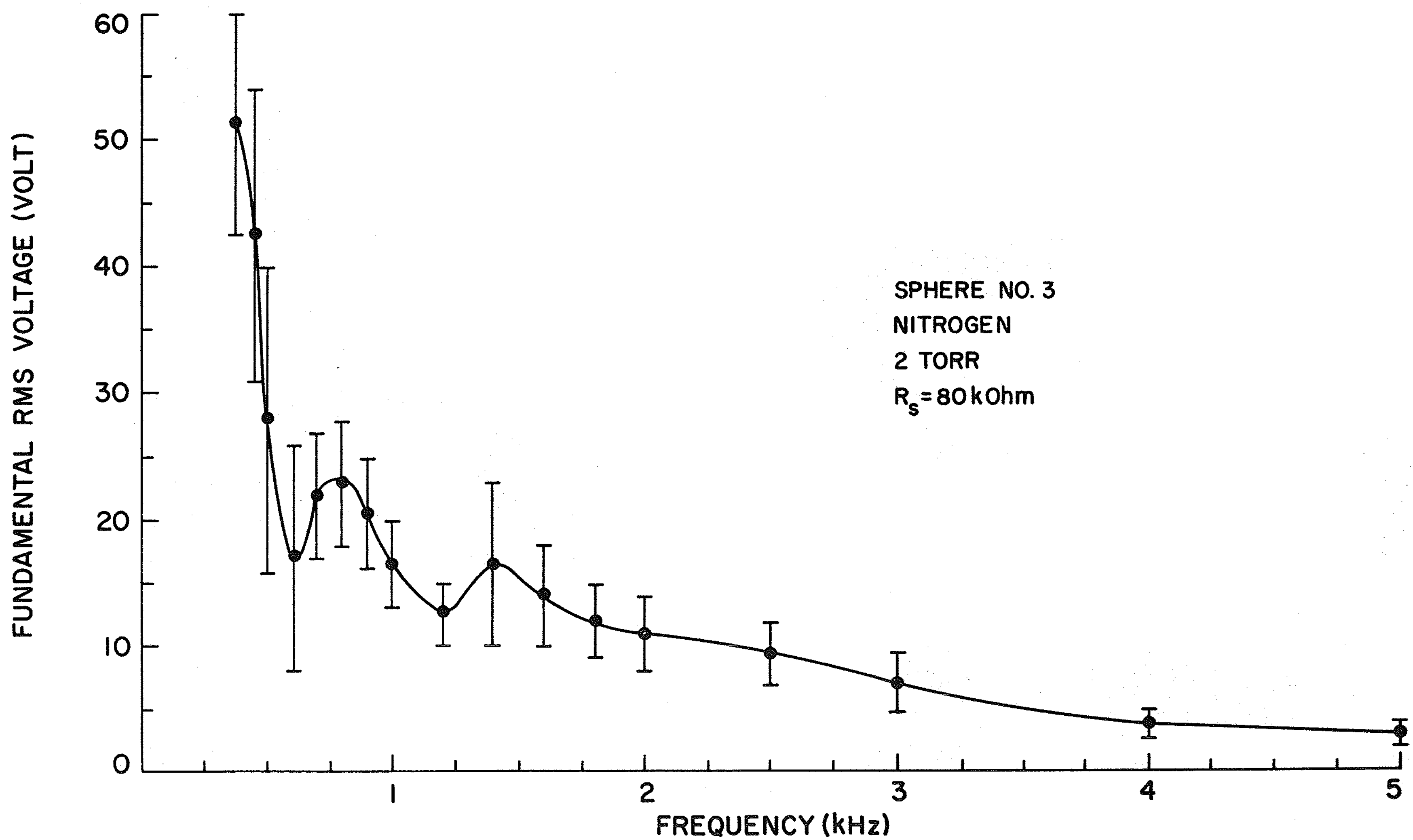
DC Voltage vs Frequency

FIGURE 3.2



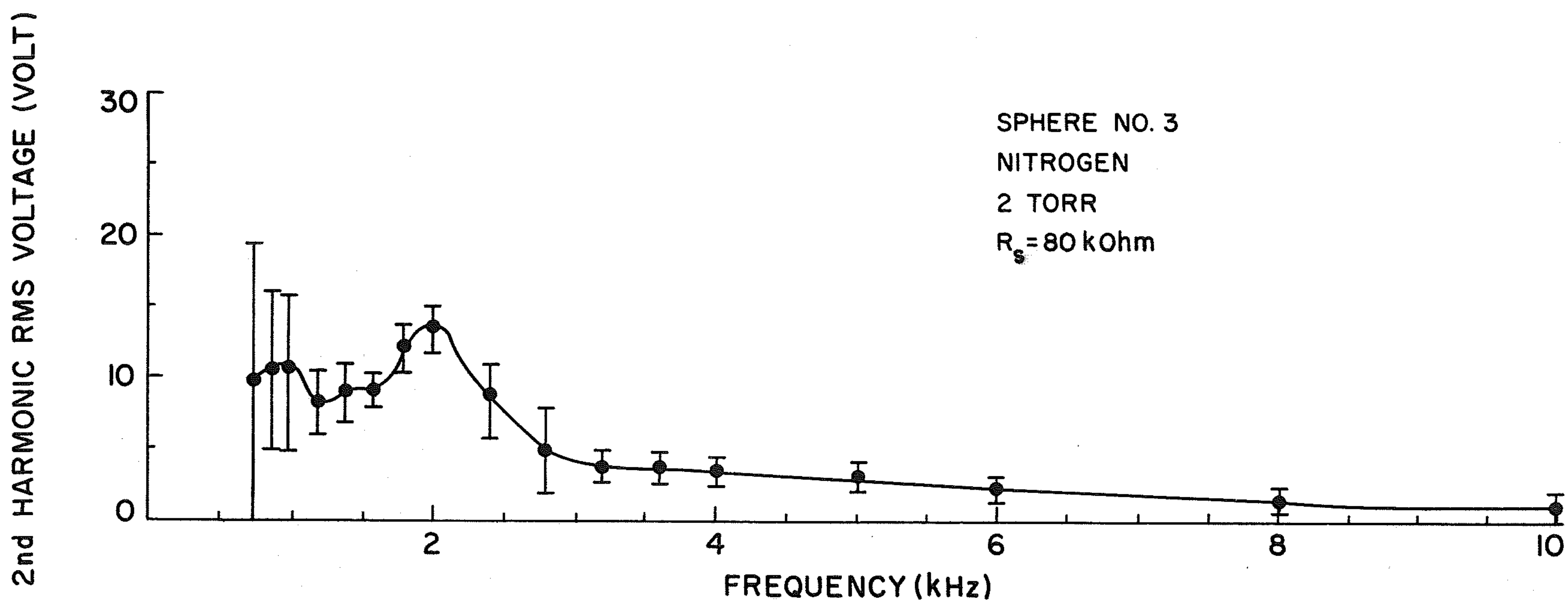
DC Current vs Frequency

FIGURE 3. 3



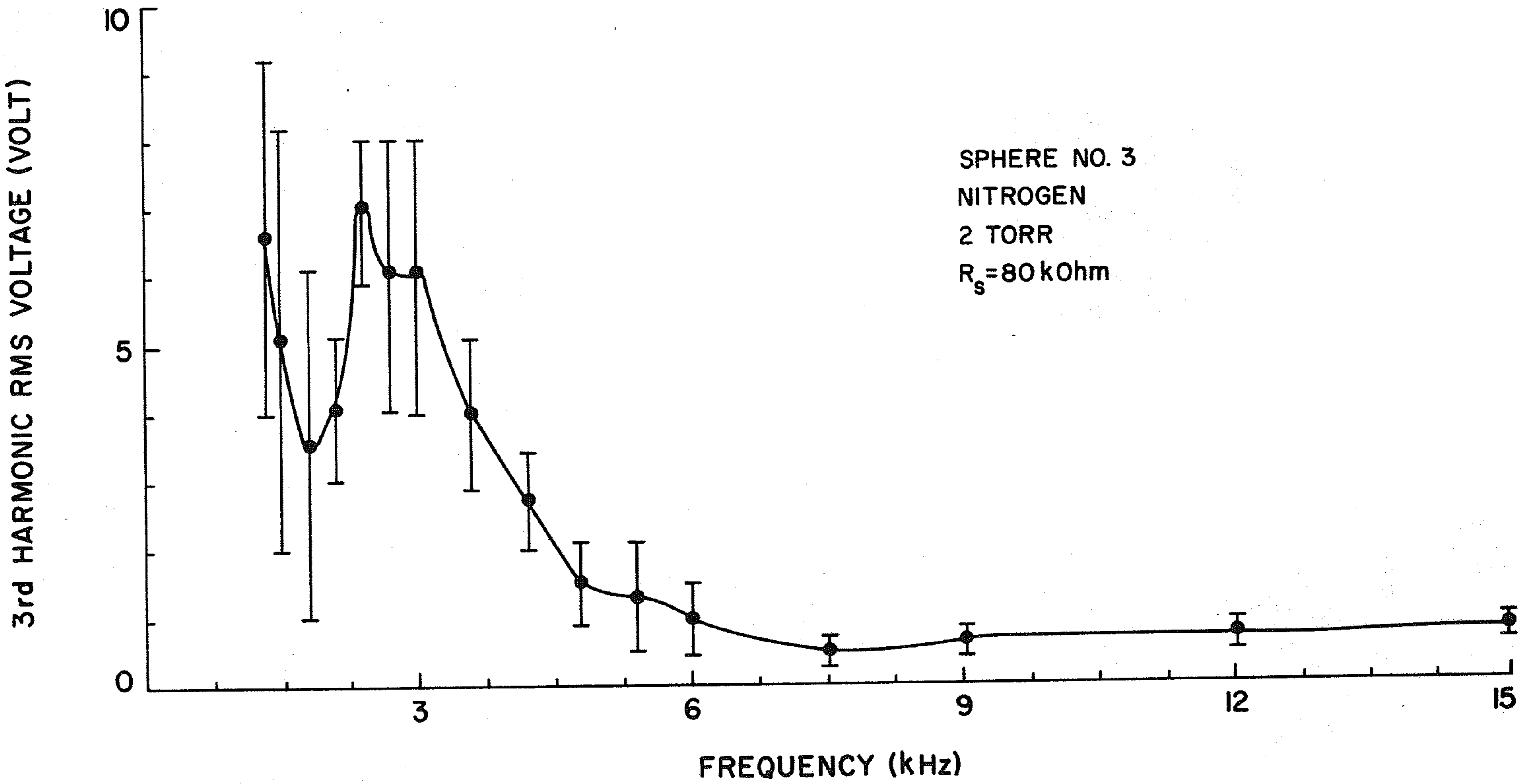
Magnitude of the Fundamental vs Frequency

FIGURE 3.4



Magnitude of the 2nd Harmonic vs Frequency

FIGURE 3.5



Magnitude of the 3rd Harmonic vs Frequency

FIGURE 3.6

maximum and minimum. The maximum occur at 2.4 kHz which corresponds with the 2nd maximum of the fundamental at 0.8 kHz. The same happens for the minima at respectively 1.8 kHz and 0.6 kHz. Comparing the fundamental with the 2nd harmonic, it is observed that the last maximum of the fundamental occurs at 1.4 kHz while for the 2nd harmonic this occurs at 2.0 kHz.

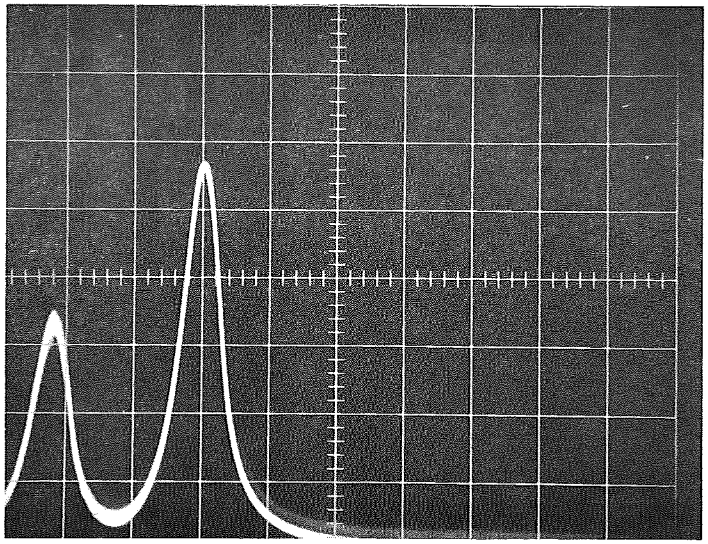
The fundamental, 2nd harmonic and 3rd harmonic of the plasma oscillations behave in the same manner for frequencies higher than 2.0 kHz. That is, they all decrease in magnitude with increasing frequency.

At the high frequency side of the spectrum, the limit is attained just before the plasma quenches. The lowest frequency is reached for large currents. The plasma oscillations disappear by increasing the current further.

Pictures 3.7 a and b are the spectrum and the time domain given for a 2.2 kHz signal from a hp model 200 CD wide range oscillator. Each pulse in the frequency domain has to be considered as a delta pulse. One may not interpret the base of the pulse as a bandwidth. To illustrate better this point the signal has been given also in the time domain.

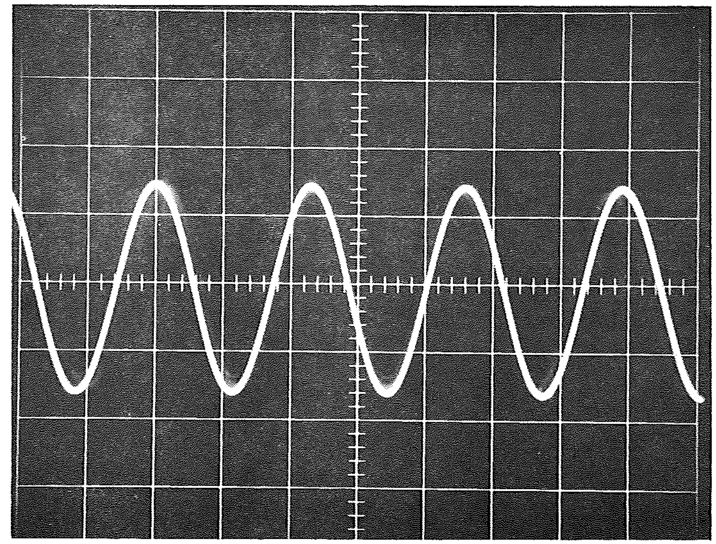
Pictures 3.8 a and b are respectively the spectrum and the time domain of the plasma oscillation with a fundamental frequency of approximately 2.3 kHz.

Similar pictures are 3.9 a and b representing a 4.6 kHz plasma oscillation in the frequency and time domain respectively.



(a)

First pulse is the zero marker
Horizontal scale, 1 kHz /div.
Vertical scale, 0.2 rms Volt /div.

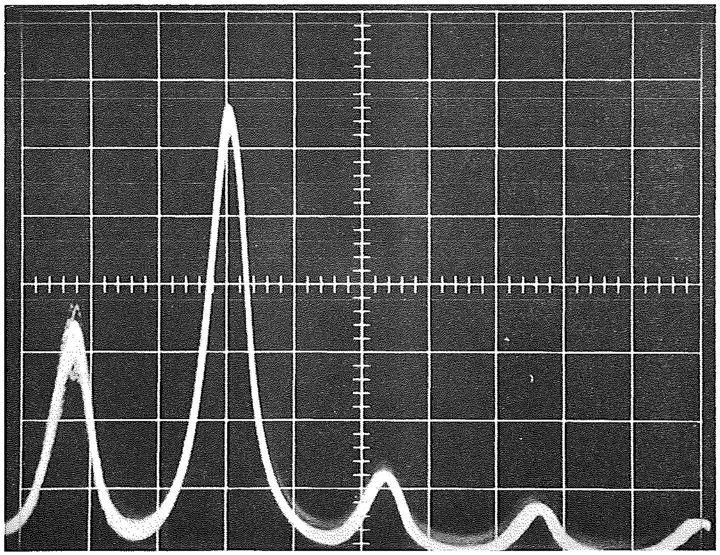


(b)

Horizontal scale, 2 m sec /div.
Vertical scale, 1 Volt /div.

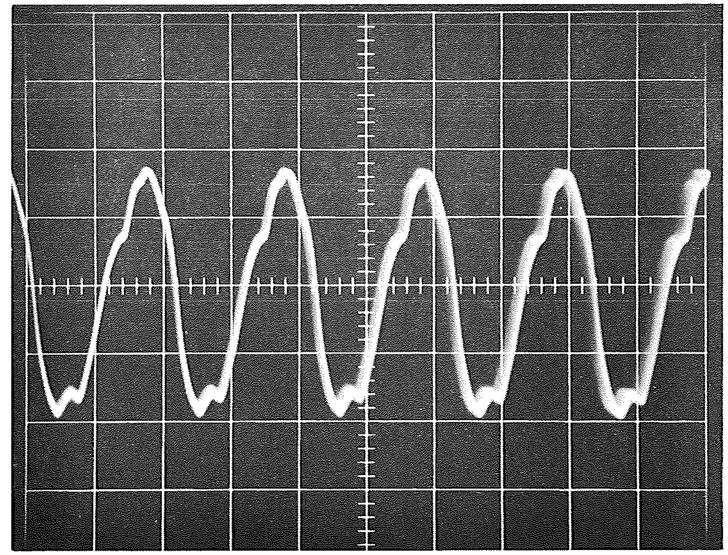
Spectrum and Waveform of 2.2 kHz Signal From Standard Generator

FIGURE 3.7



(a)

First pulse is the zero marker
Horizontal scale, 1 kHz /div.
Vertical scale, 2 rms Volt /div.
V_{DC} = 940 Volt, $I_{DC} \approx 1.2$ mA, R_s = 80 kohm, Sphere No. 3, 2 Torr.

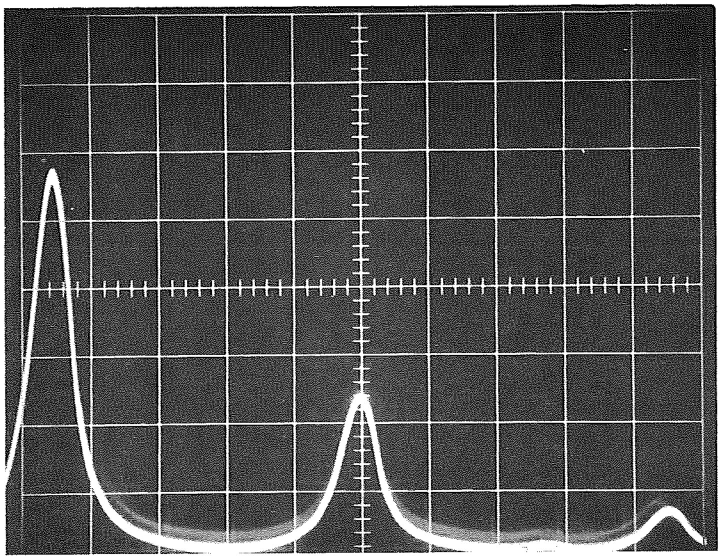


(b)

Horizontal scale, 2 m sec /div.
Vertical scale, 10 Volt /div.
V_{DC} = 940 Volt, I_{DC} = 1.2 mA, R_s = 80 kohm, Sphere No. 3, 2 Torr.

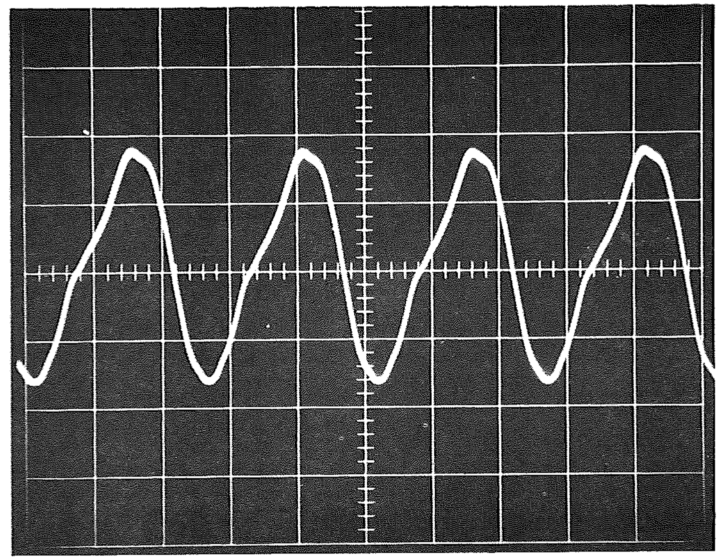
Spectrum and Waveform of 2.3 kHz Nitrogen Plasma Oscillation

FIGURE 3.8



(a)

The first pulse is the fundamental
Horizontal scale, 1 kHz /div.
Vertical scale, 0.5 rms Volt /div.
V_{DC} = 945 Volt, I_{DC} = 0.8 mA,
R_s = 80 kohm, Sphere No. 3, 2 Torr.



(b)

Horizontal scale: 0.1 m sec /div.
Vertical scale: 5 Volt / div.
V_{DC} = 945 Volt, I_{DC} = 0.8 mA, R_s = 80 kohm, Sphere No. 3, 2 Torr.

Spectrum and Waveform of 4.6 kHz Nitrogen Plasma Oscillation

FIGURE 3.9

For frequencies below 1.0 kHz, it is found that small arcs occur at the cathode surface. These arcs seem to interfere with the plasma ring current. The observed spectrum becomes ill defined as shown in figures 3.10 a and b.

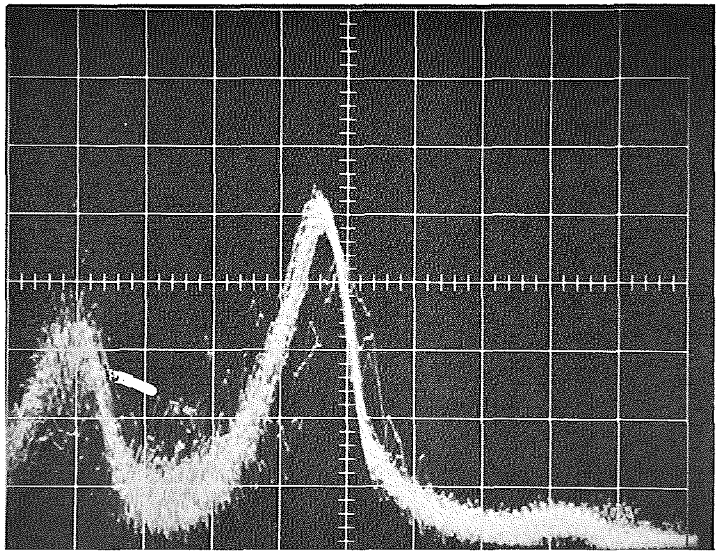
All photographs were taken using a Type 564 storage oscilloscope, with a type 2B67 time base, type 3L-5 spectrum wave analyzer and a C.12 oscilloscope camera from Tektronix. The film used is polaroid 3000, type 47.

The curves in figures 3.2 to 3.6 are obtained in the following manner. The experiment is repeated several times. The data points are plotted and connected by straight lines. The error in frequency is assumed to be negligible so that the only uncertainty taken into consideration is the magnitude of the signal. A further assumption is made that each of the runs has equal probability. And that after 4 runs the possible extremes in magnitude have occurred. An average is then obtained by locating the point in the center of the uncertainty region defined by the upper and lower extreme curves. The average curve is obtained by connecting the average points by means of a smooth line.

3.1.2 The Effect of Pressure upon the Plasma Oscillations

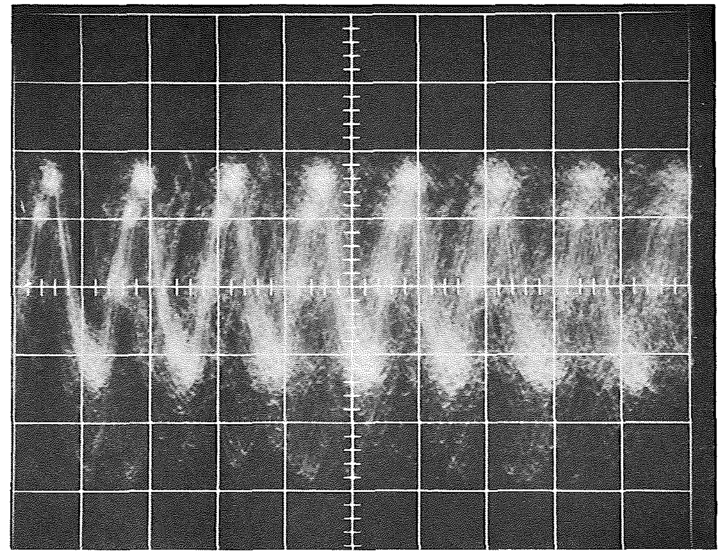
The results plotted in figures 3.11 to 3.15 refer to data obtained in a similar experiment as described in 3.1.1 using sphere no. 3 and nitrogen as the residual gas but at a pressure of 1.0 torr.

Comparing curves A and B in figure 3.1, one notices that the discharge characteristic for 1.0 torr is shifted toward the low voltage side.



(a)

First pulse is the zero marker
Horizontal scale, 100 Hz /div.
Vertical scale, 10 rms Volt /div.
V_{DC} = 710 Volt, I_{DC} = 8.5 mA, R_s = 80 kohm, Sphere No. 3, 2 Torr.

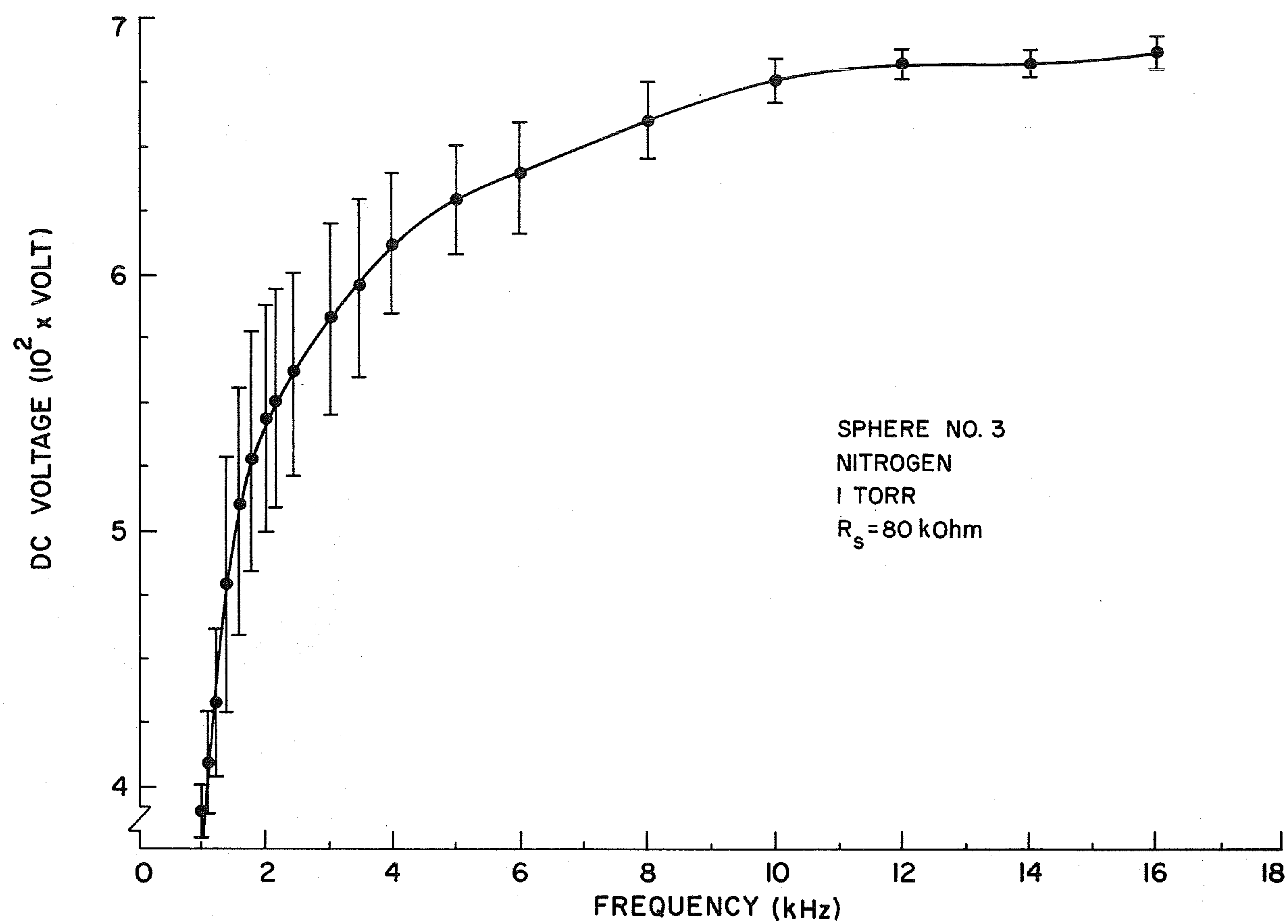


(b)

Horizontal scale, 2 m sec /div.
Vertical scale, 50 Volt /div.
V_{DC} = 710 Volt, I_{DC} = 8.5 mA, R_s = 80 kohm, Sphere No. 3, 2 Torr.

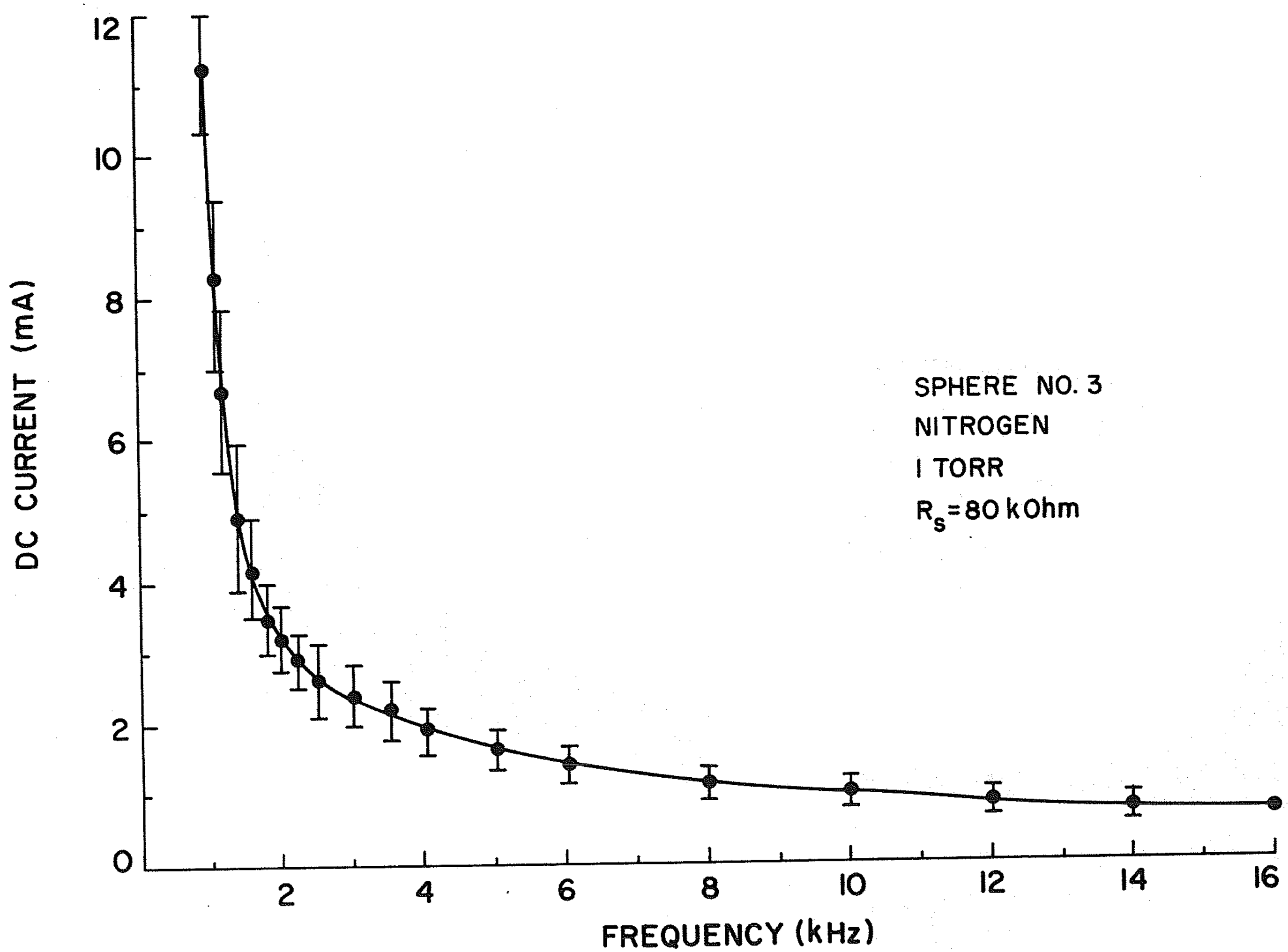
Spectrum and Waveform of 0.35 kHz Nitrogen Plasma Oscillation

FIGURE 3.10



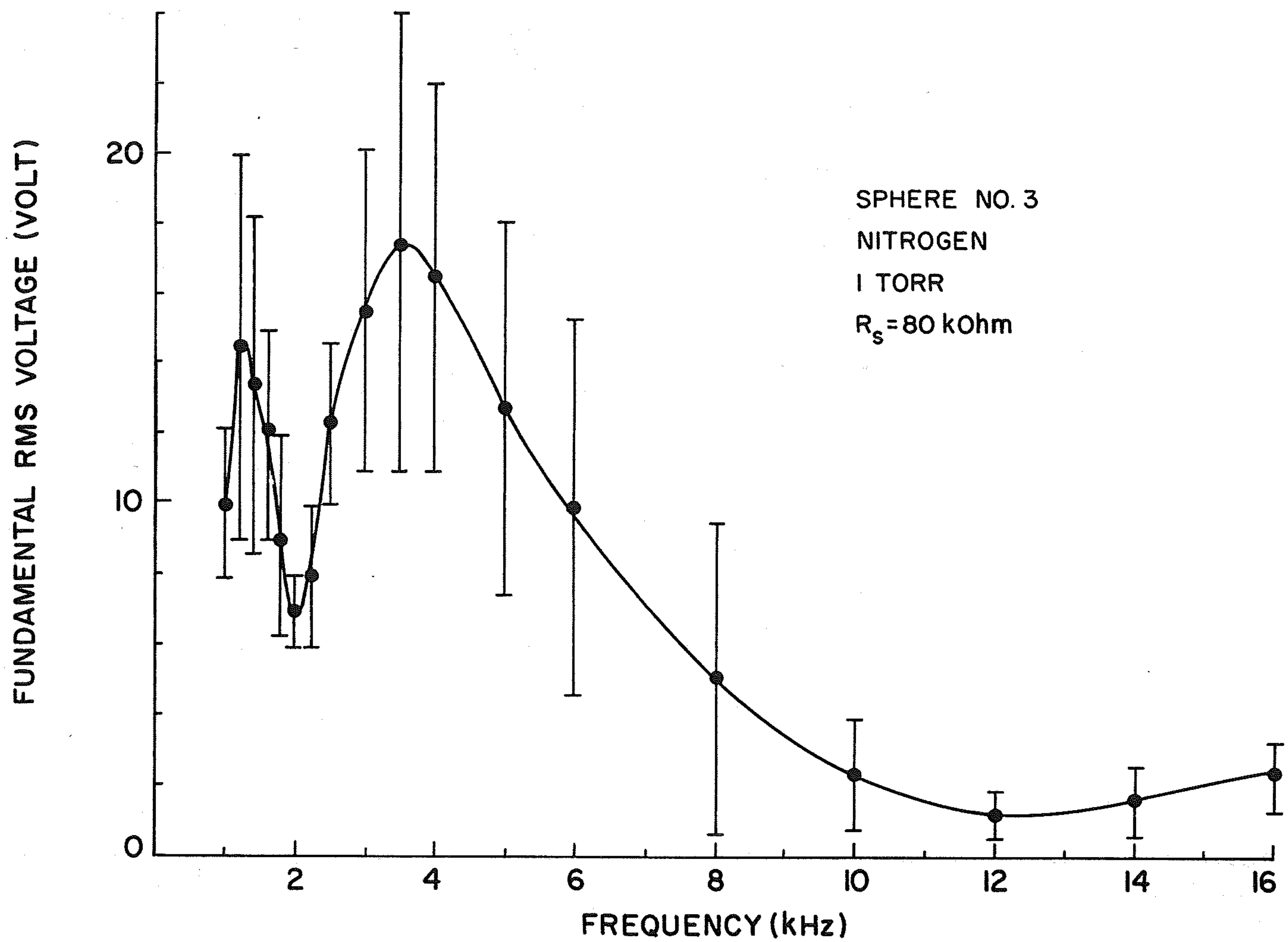
DC Voltage vs Frequency

FIGURE 3.11



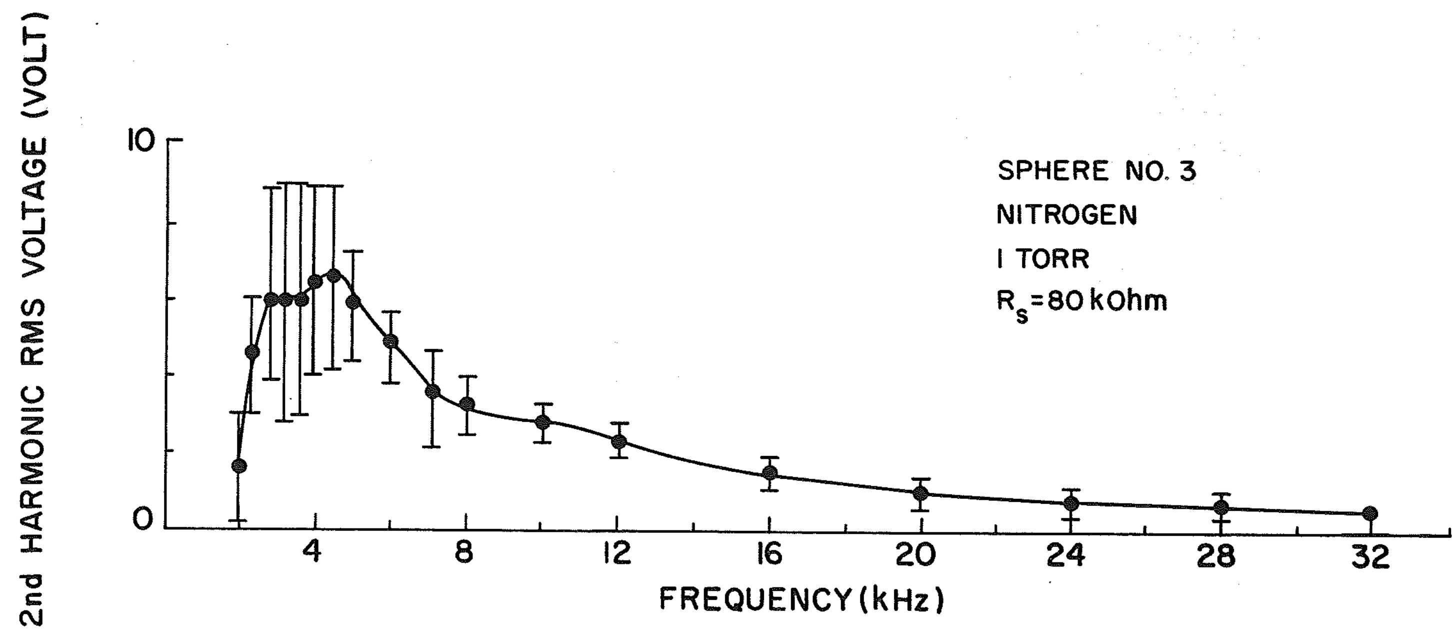
DC Current vs Frequency

FIGURE 3.12



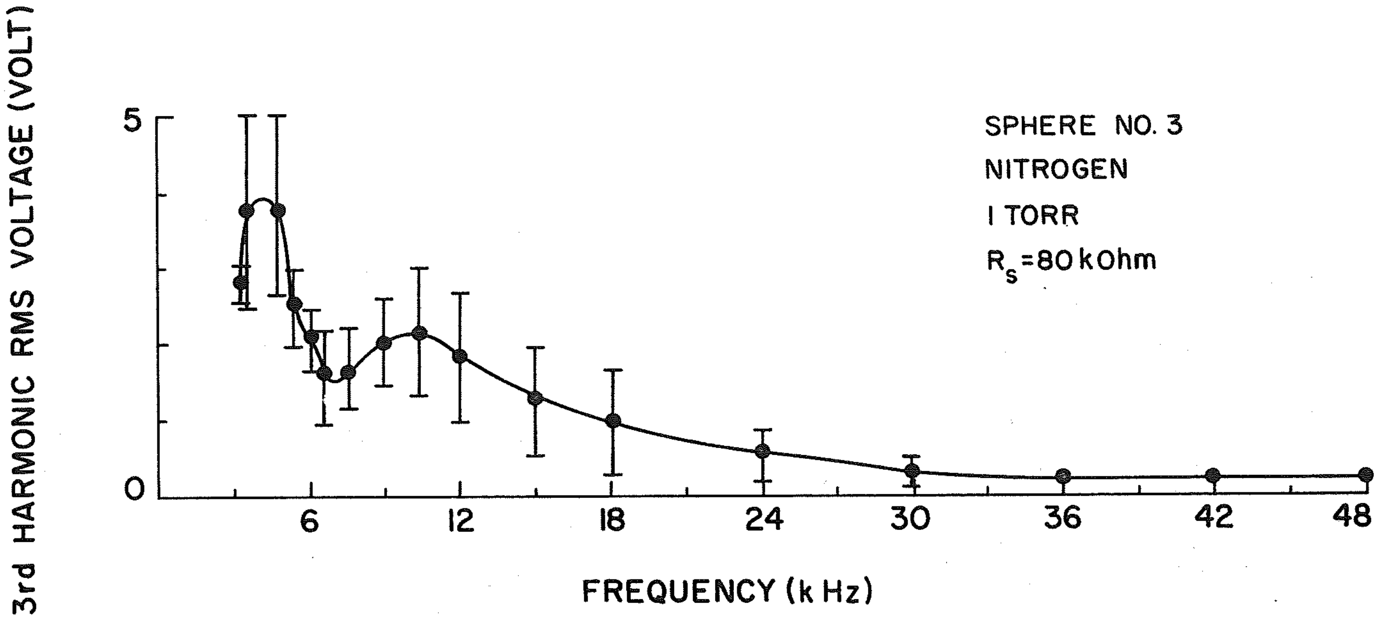
Magnitude of the Fundamental vs Frequency

FIGURE 3.13



Magnitude of the 2nd Harmonic vs Frequency

FIGURE 3.14



Magnitude of the 3rd Harmonic vs Frequency

FIGURE 3.15

Figures 3. 11 and 3. 12 show that the frequency extends from 16 kHz to approximately 1 kHz. And that a decrease in pressure causes an increase in frequency.

Again the plasma oscillations with the lowest frequency are obtained for high DC current and low DC voltage. The general form of the curves is the same for both pressures.

More pronounced differences are observed between the figures 3. 4, 3. 5 and 3. 6 and respectively 3. 13, 3. 14 and 3. 15. The decrease in pressure to 1 torr causes the amplitude of the plasma fluctuations to increase at high frequency, e. g. at 3500 Hz, the magnitude of the fundamental is in the range of 17 rms volt at 1 torr, while for the same frequency at 2 torr the magnitude is in the range of 5 rms volt. On the other hand it is observed that the smallest magnitude at 1 torr occuring at 12 kHz is in the range of 0. 6 rms volt while the smallest observed magnitude at 2 torr is in the range of 3 rms volt at 5 kHz. Further the same general features are observed as previously at 2 torr. The low frequency side of the curves is marked again by minima and maxima while at the high frequency side the magnitudes are continuously decreasing.

3. 1. 3 The Effect of the Series Resistance (R_s)

The experiment, as described in 3. 1. 1 is repeated for a series resistance of 160 k ohm.

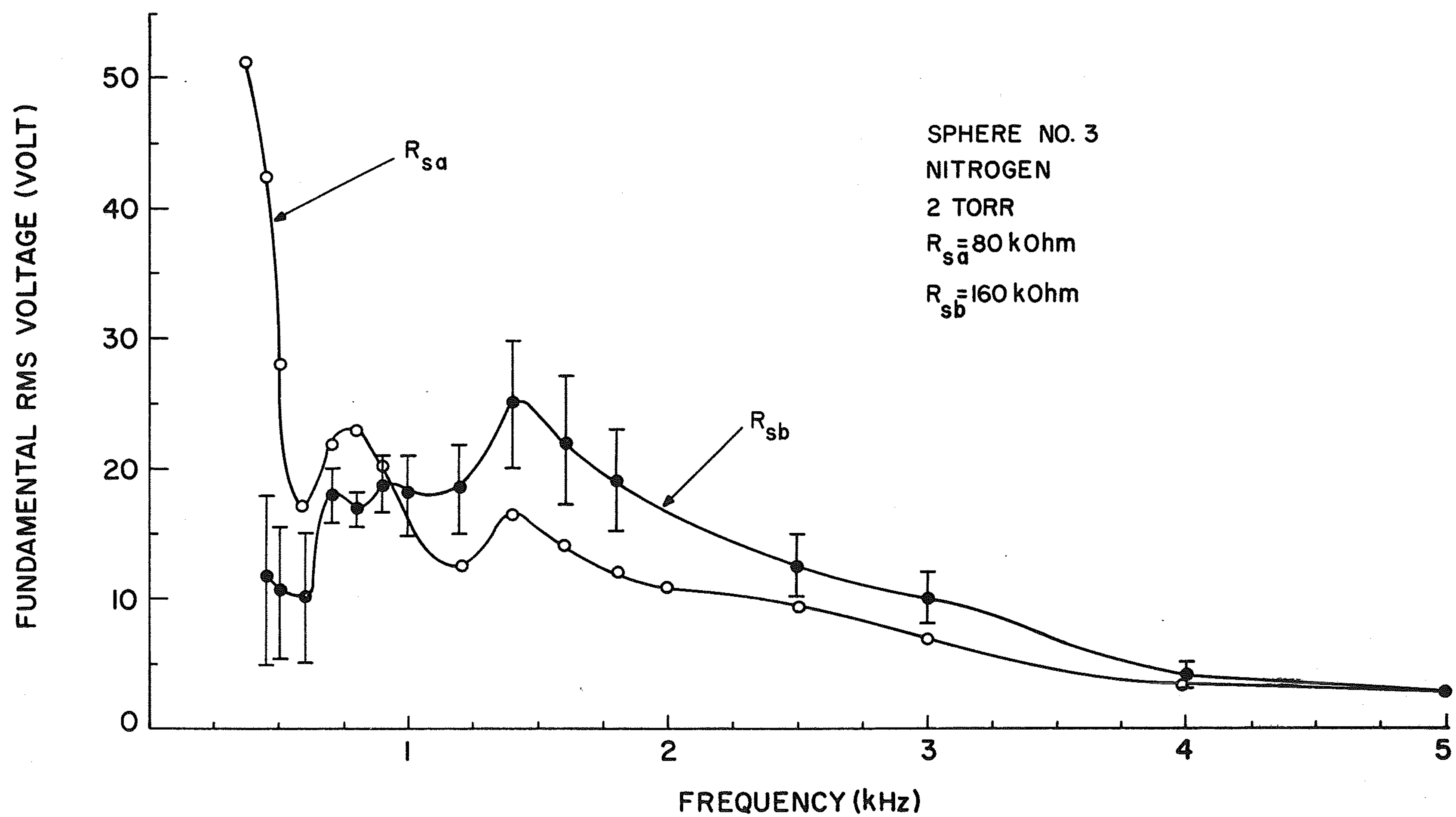
The discharge characteristic is not appreciably changed. The only difference occurs at the high current and low voltage side which does not extend up to the point obtained previously but this is due to the limitation imposed by the used power supply. Further the curve falls within the region specified by the error bars of the average discharge characteristic obtained for the plasma at 2 torr as depicted in figure 3. 1, curve B and curve C.

In figures 3. 16, 3. 17 and 3. 18 the magnitude of the fundamental, 2nd harmonic and 3rd harmonic in rms voltage are plotted versus frequency for R_s = 160 kohm.

In order to make the comparison easier, the previously obtained curves for R_s = 80 kohm are also presented. For simplicity, the error bars have been omitted.

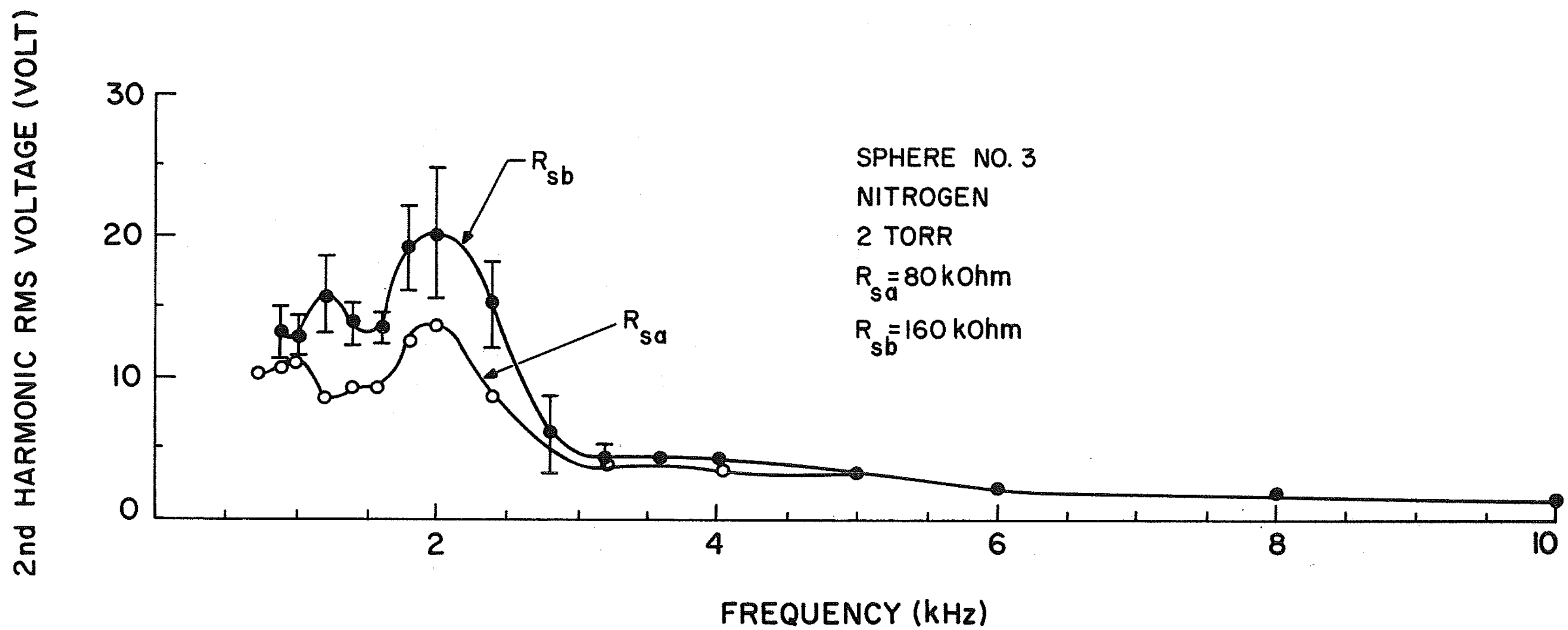
These results indicate that the frequency of the fluctuation is independent of the external resistor.

Further it is noticed that the magnitude changes but not in the ratio of 2:1 as the resistor values. For a pressure of 2 torr, it is found that, taking into account the error bars, the magnitudes of the fundamental of the plasma oscillations are approximately equal for the frequency range of 2. 5 to 5. 0 kHz. The 2nd and 3rd harmonic show better agreement. In other words the device can be considered as a constant voltage generator for the high frequency part of the spectrum. From figures 3. 2 and 3. 3 one sees that this corresponds to the region where the DC current and DC voltage are in the first approximation constant.



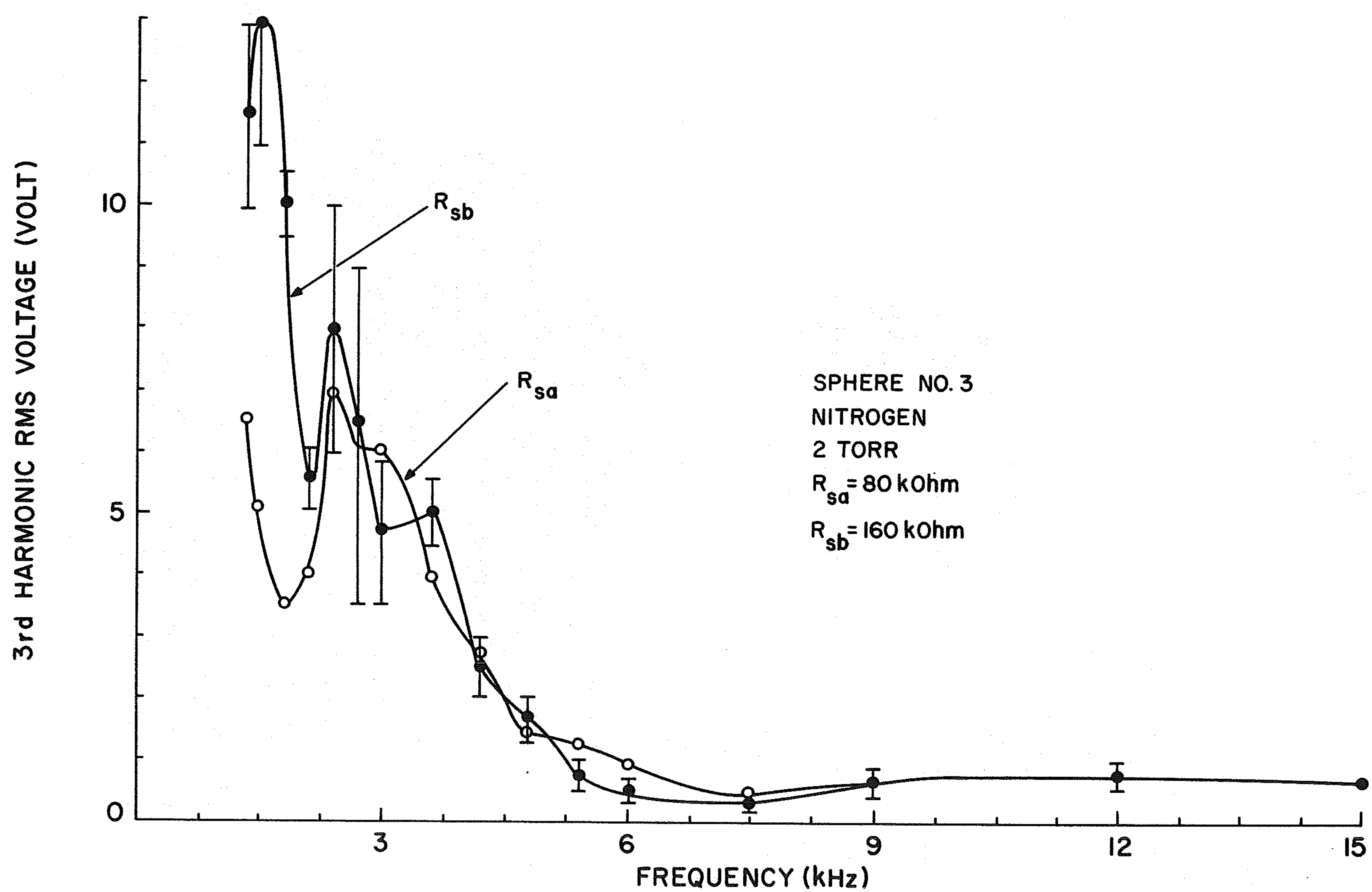
Magnitude of the Fundamental for Different Serie Resistance Values vs Frequency

FIGURE 3.16



Magnitude of the 2nd Harmonic for Different Serie Resistance Values vs Frequency

FIGURE 3.17



Magnitude of the 3rd Harmonic for Different Serie Resistance Values vs Frequency

FIGURE 3. 18

At the low frequency side, it is observed that an increase in R_s suppresses the magnitude of the fundamental and increases the magnitude of the 2nd harmonic. At 1.0 kHz, the magnitude of the 2nd harmonic becomes even larger than the magnitude of the fundamental. Similar features are observed for a pressure of 1 torr. In that case, the 2nd harmonic becomes larger than the fundamental at 2 kHz and the plasma device can be looked at as a constant voltage generator for the frequency range of 6.0 to 14.0 kHz. The spectrum range for which the noise amplitude is independent of the exterior resistor occurs when the plasma resistor R_{DC}, defined as the ratio of DC voltage to DC current, is much larger then R_s, the exterior resistor.

3.1.4 Effect of Magnetic Fields

3.1.4.1 Effect of the Magnetic Field on the Formation of the Plasma Belt

In order to determine whether the magnetic field is a necessary condition for the V.L.F. plasma oscillations to exist, the magnetized sphere was replaced by an unmagnetized one. Sphere no. 1 (see table 1.1) has been used and it is noticed that the plasma configuration associated with the oscillation does not exist. The plasma is not located in the equatorial plane but covers the complete sphere at low pressures. At the pressures of interest; i.e. 1.0 and 2.0 torr with nitrogen as the residual gas the spherical cathode is only partially covered under maximum discharge condition, i.e., I_{DC} maximum, and V_{DC} minimum. The covered area decreases with a decrease in DC current as one readily expects. No VLF frequency plasma noise is observed under any condition of pressure, DC voltage and DC current.

By changing the unmagnetized sphere no. 1 for the magnetized sphere no. 4 with the strongest magnetic field available, it is noticed that no normal plasma ring is formed at the equator at 1.0 and 2.0 torr. At 0.5 torr the sphere is completely covered and a plasma ring in the equator becomes visible. By decreasing the current the plasma ring is first broken while the sphere is covered with a plasma glow. By decreasing the pressure and under maximum discharge condition the plasma is confined to the equatorial plane. Only random noise no discrete tones, becomes audible. The noise disappears by decreasing the current or by further decreasing the pressure. It results thus that, for a strong magnetic field a belt plasma is formed at low pressures.

Decreasing the magnetic field by using sphere no. 3, we see that a plasma belt starts forming at 2.5 torr. At 2.0 torr and 1.0 torr a very clear audible noise is observed as discussed in the previous paragraphs.

Going over to a still weaker magnetic field by using sphere no. 2 the plasma belt is formed up to approximately 4.5 torr.

From these series of experiments one can conclude that a magnetic field is necessary in order to get a dense plasma ring appearing in the equatorial plane associated with the V.L.F. fluctuations. And further that, for a fixed pressure, there exists a B field above which no plasma belt can form.

3.1.4.2 The Effect of Magnetic Field Upon the Plasma Oscillations

Due to the fact that different spheres have different surface conditions in addition to different crystalline structure, it is not possible to make a complete detailed comparison between the plasma oscillations obtained for different spheres. However, the following observations have been made.

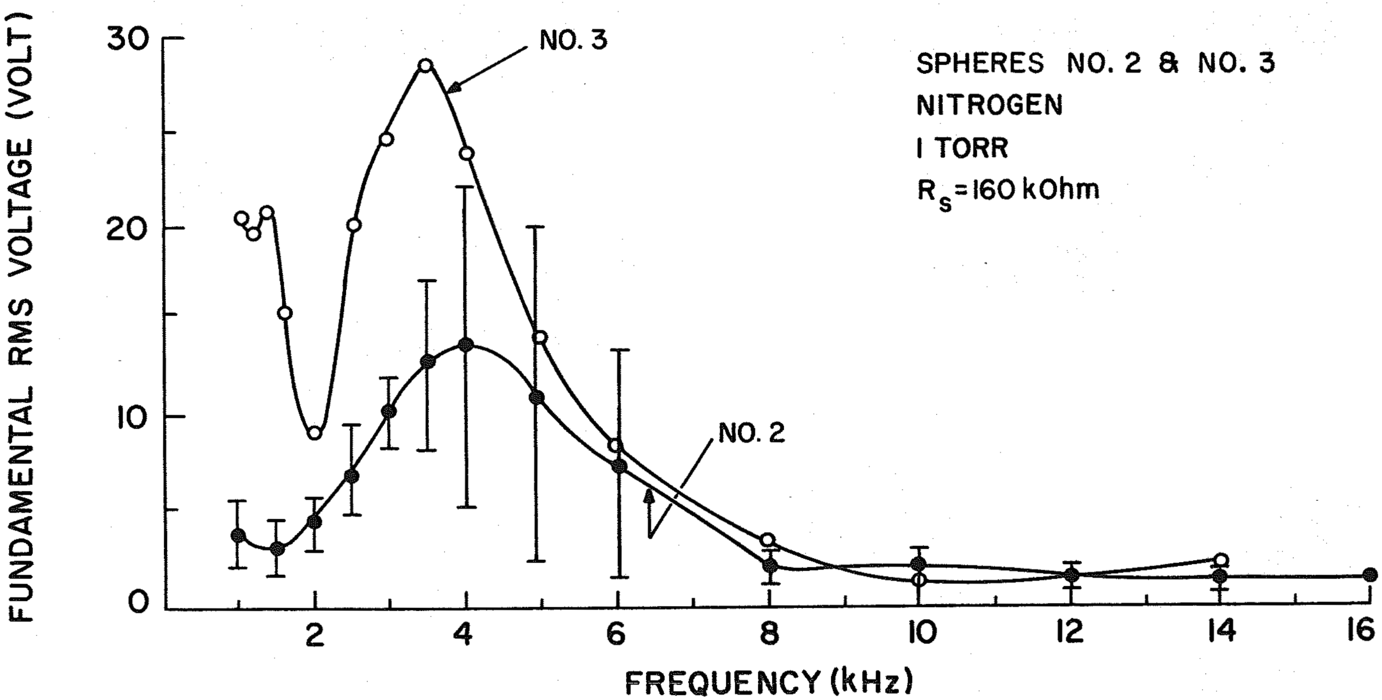
Figure 3.19 shows the magnitudes of the fundamental of the plasma fluctuations versus frequency obtained respectively for spheres no. 2 and no. 3. The curves are represented without error bars. The most important feature that appears from this graph is that the frequency range is identical (within the experimental error) for both spheres. Briefly, the frequency of the plasma oscillations is independent of the magnetic field within experimental accuracy.

There seems to exist an influence of the magnetic field upon the amplitude at the low frequency side although no strict comparison as such is possible due to the different discharge characteristics obtained respectively with different spheres.

3.1.5 Effect of Various Ion Species

3.1.5.1 Argon

Performing the experiment with argon as a residual gas one sees that for a pressure larger than 1 torr sphere no. 3 is partially covered. By decreasing the current the covered area decreases as long as V_{DC} stays constant. At the moment V_{DC} increases the plasma start vibrating i.e. the plasma dot shows vibrating extremeties and takes on an ellongated form in the equatorial plane and finally a visible plasma ring is formed. At that moment VLF oscillations are observed. For a pressure below 1 torr a completely covered sphere with a dense ring zone in the equatorial plane is noticed. In this case, decreasing the current will first break up the dense ring zone and next cause the covered area to decrease. No V.L.F. oscillation is observed under these conditions.



Magnitude of the Fundamental for Different Magnetic Fields vs Frequency

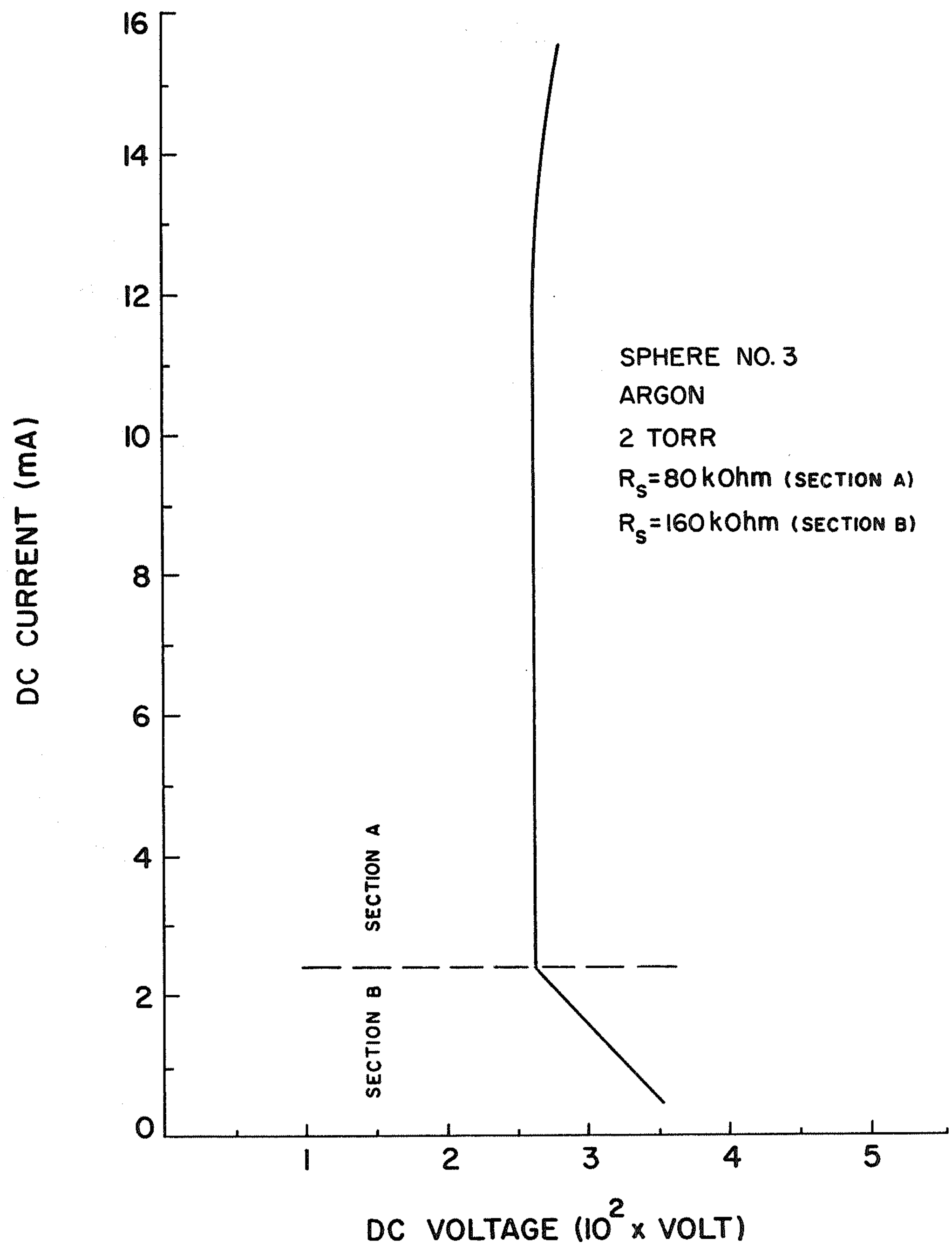
FIGURE 3.19

Figures 3.20, 3.21 and 3.22 show the data obtained for sphere no. 3. As shown schematically in figure 3.20 two values of R_s have been used for the discharge characteristic. For $R_s = 80$ kohm the high current part of the characteristic is obtained. The plasma quenches at low DC current levels. For this part of the curves no VLF oscillations are found. The low current part of the curve is obtained with $R_s = 160$ kohm. Also for this value of DC resistance, VLF oscillations are not observed for $I_{DC} > 2mA$. For the graphs 3.21 and 3.22 only the value of 160 kohm is used.

In figure 3.21, DC current and DC voltage versus frequency are presented. One distinct difference with the argon data is found, i.e., the lower limit of the spectrum extends to 50 Hz (limit of the spectrum wave analyzer). Further the upper frequency limit is the same as that for nitrogen.

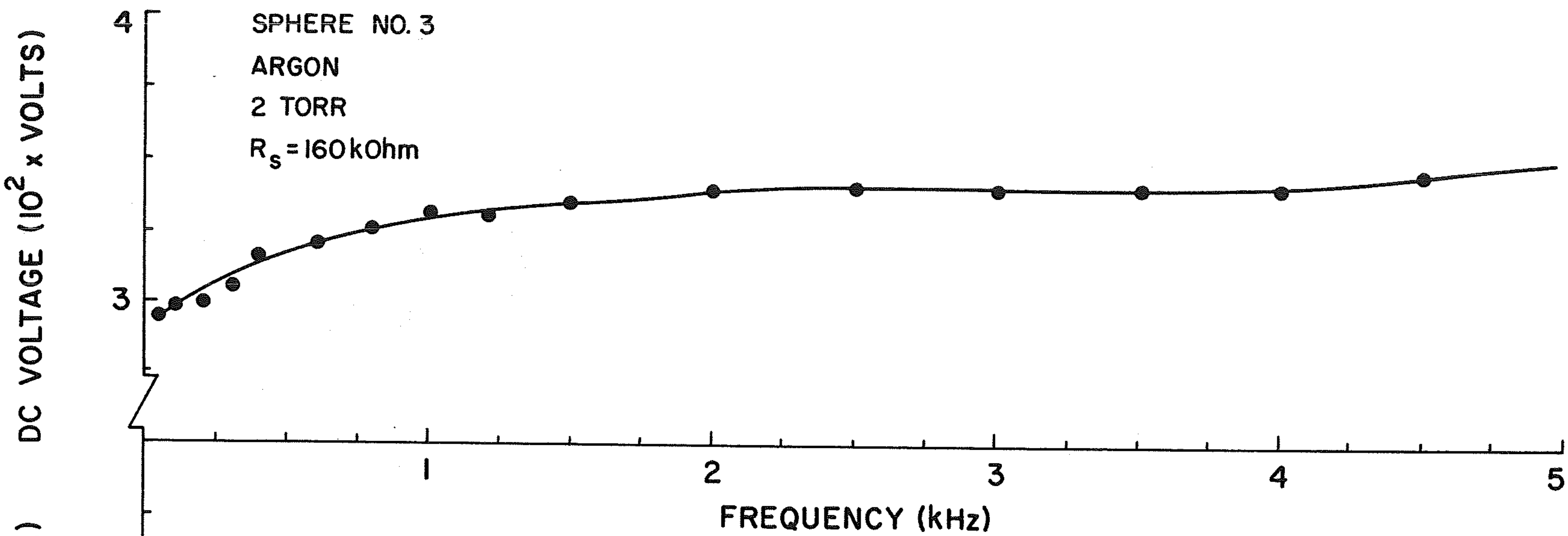
The fundamental, the 2nd harmonic and 3rd harmonic in rms volt versus frequency are plotted in figure 3.22. The curves are again characterized by maxima and minima. It is seen that the maximum magnitude of the fundamental is much smaller for argon then for nitrogen.

In figure 3.23, pictures a and b are respectively the spectrum and time domain of the plasma oscillations with a fundamental frequency of 2.3 kHz. Figures 3.24 a and b concern plasma oscillations with 4.6 kHz as fundamental frequency. Comparing with the pictures given in figure 3.8 and 3.9 for nitrogen it is noticed that at 2.3 kHz the nitrogen plasma oscillations are less rich in harmonic while at 4.6 kHz the reverse seems to happen.

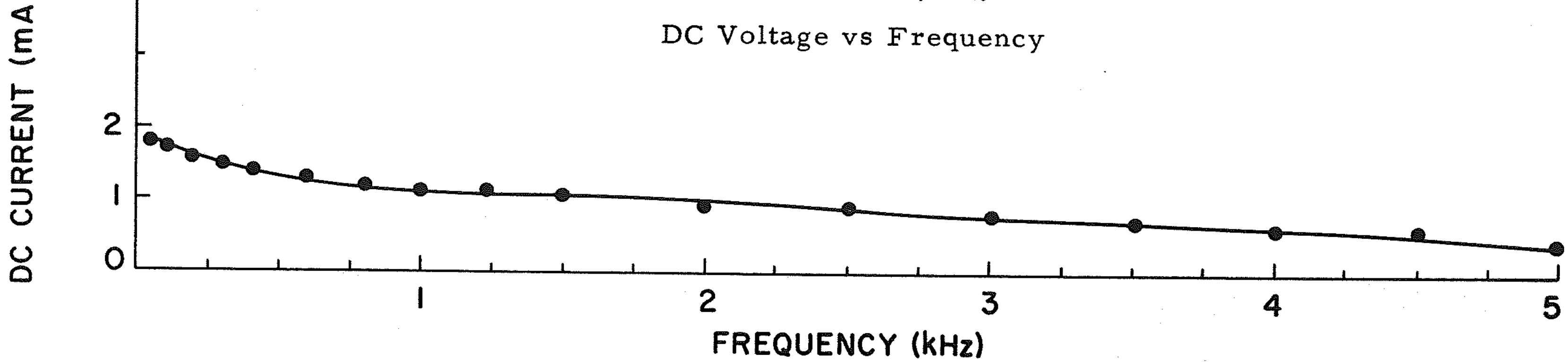


DC Discharge Characteristic

FIGURE 3.20

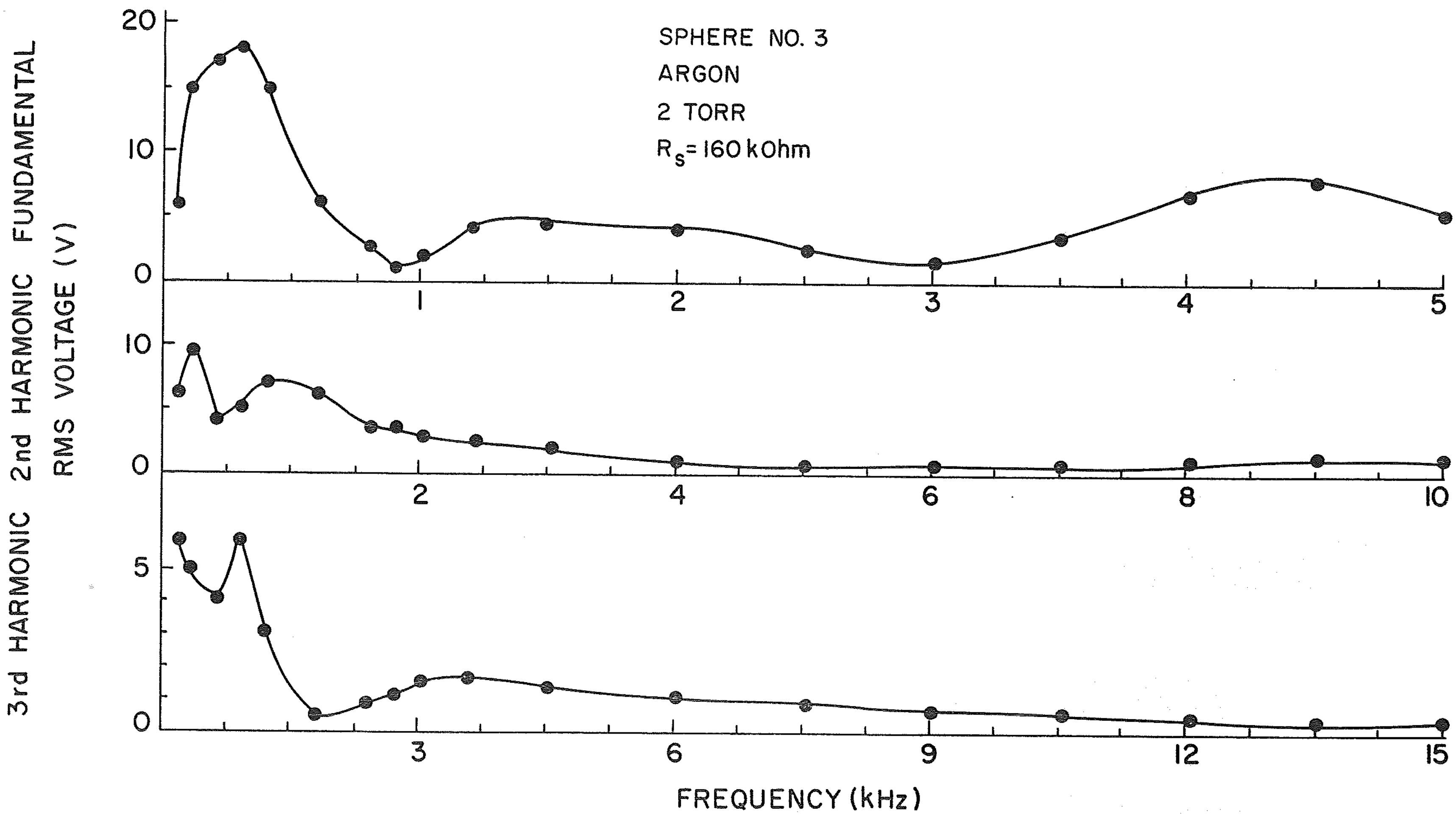


DC Voltage vs Frequency



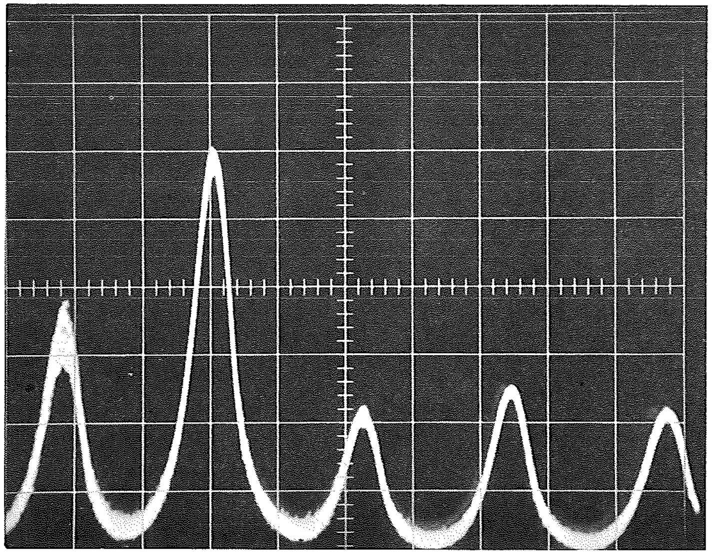
DC Current vs Frequency

FIGURE 3.21



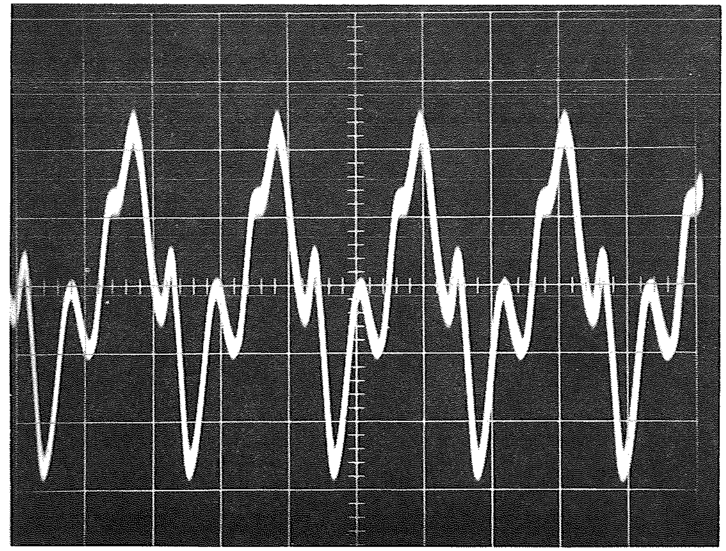
Magnitude of the Fundamental, 2nd and 3rd Harmonic vs Frequency

FIGURE 3.22



(a)

First pulse is the zero marker
Horizontal scale, 1 kHz /div.
Vertical scale, 0.2 rms Volt /div.
V_{DC} = 338 Volt, I_{DC} = 0.7 mA, R_s =
160 rohm, Sphere No. 3, 2 Torr.

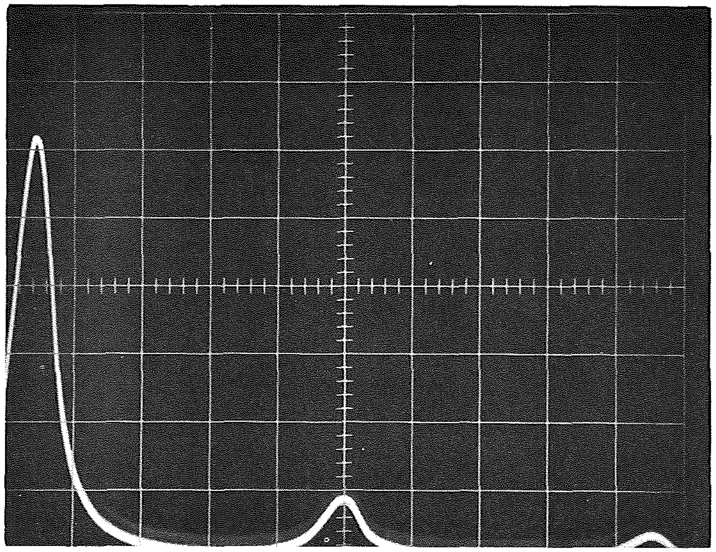


(b)

Horizontal scale, 0.2 m sec /div.
Vertical scale, 1 Volt /div.
V_{DC} = 338 Volt, I_{DC} = 0.7 mA, R_s =
160 kohm, Sphere No. 3, 2 Torr.

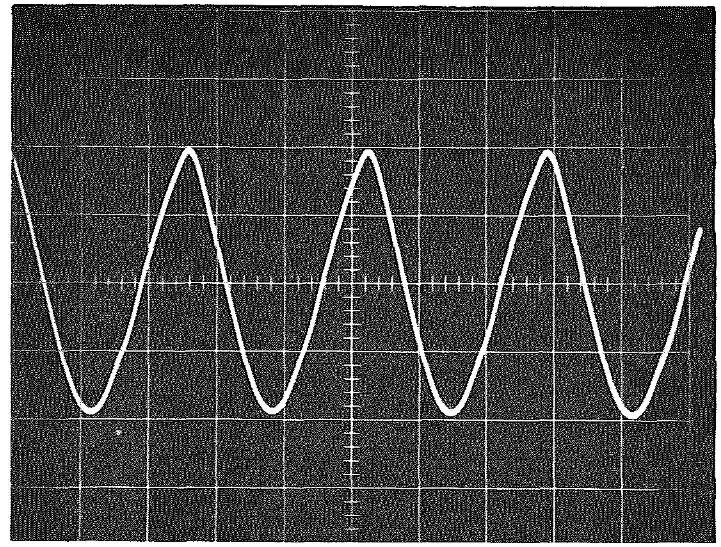
Spectrum and Waveform of 2.3 kHz Argon Plasma Oscillation

FIGURE 3.23



(a)

First pulse is the fundamental
Horizontal scale, 1 kHz /div.
Vertical scale, 0.5 rms Volt /div.
V_{DC} = 350 Volt, I_{DC} = 0.3 mA, R_s = 160 kohm, Sphere No. 3, 2 Torr.



(b)

Horizontal scale, 0.1 m sec /div.
Vertical scale, 5 Volt / div.
V_{DC} = 350 Volt, I_{DC} = 0.3 mA, R_s = 160 kohm, Sphere No. 3, 2 Torr.

Spectrum and Waveform of 4.6 kHz Argon Plasma Oscillation

FIGURE 3.24

3.1.5.2 Helium

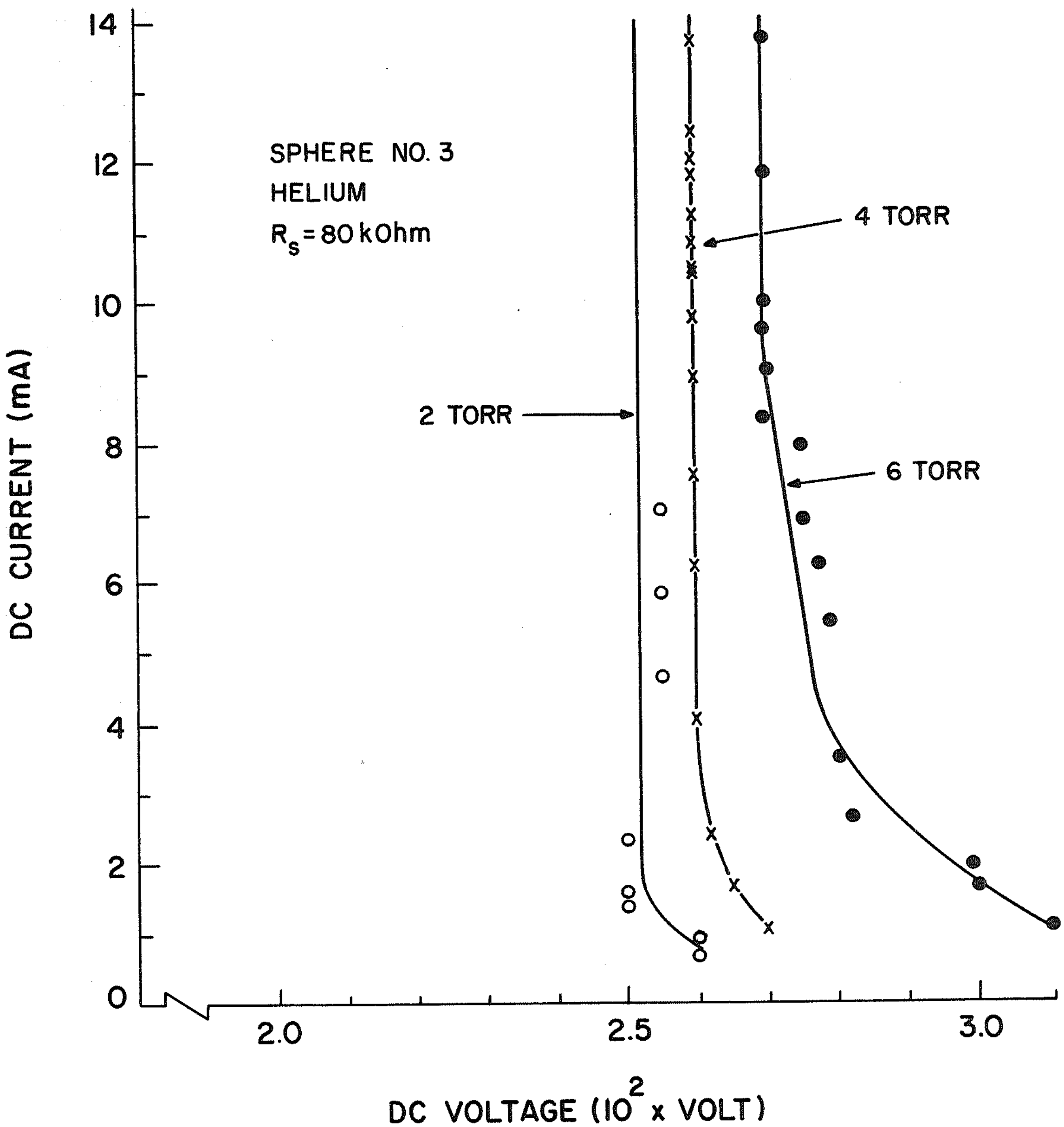
Using helium as a residual gas, it is observed that:

a) The shift of the discharge characteristics with pressure is very much smaller then the shift found for nitrogen. In figure 3.25, the discharge characteristics of helium have been plotted for pressures at 2, 4 and 6 torr.

b) From figures 3.26 to 3.29 it is noticed that several modes of plasma oscillation occur. The modes are separated by transition regions. Transition regions are here defined as regions in which a discontinuity in the change of frequency is observed. In this region overlapping of two modes is also observed as described in section f.

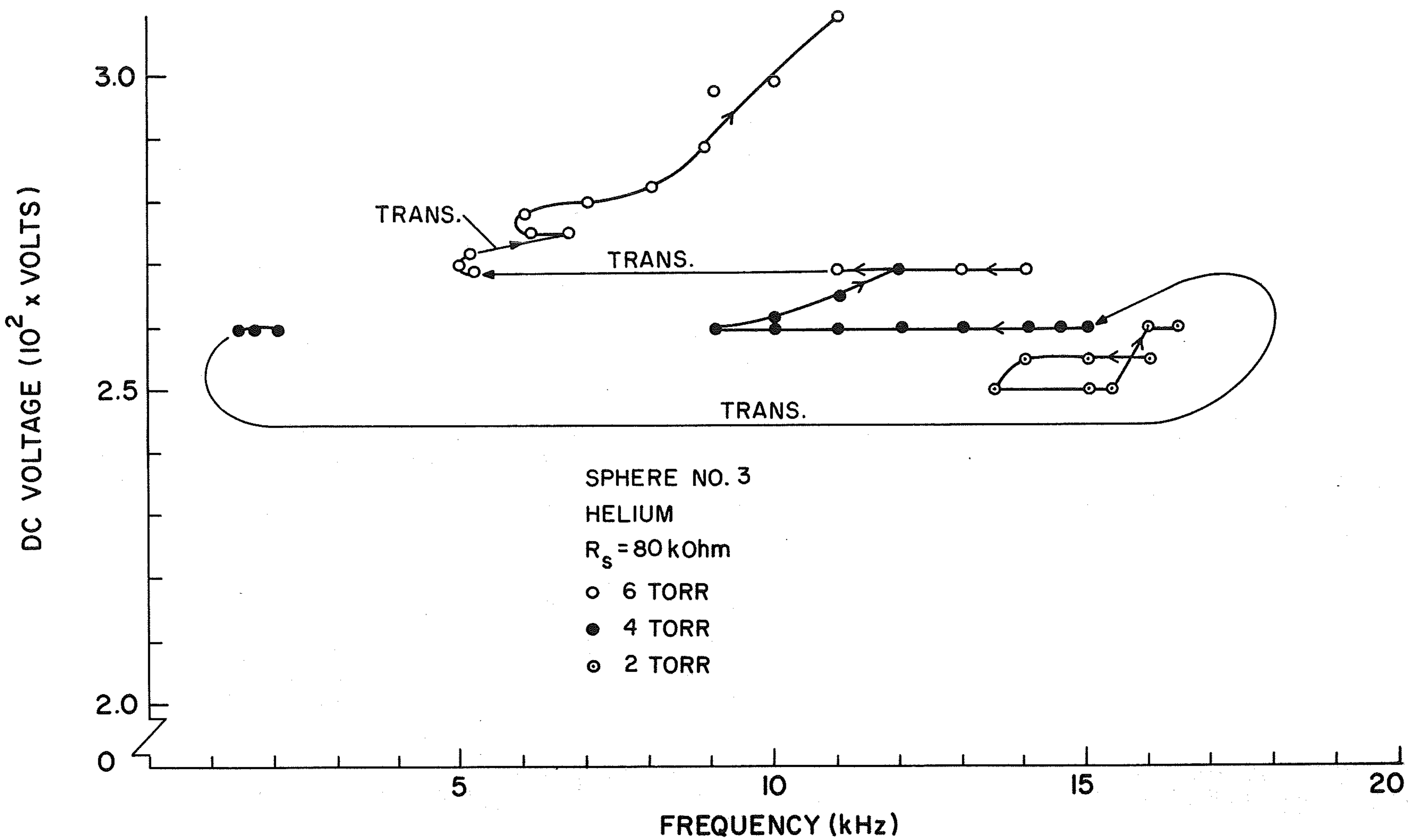
c) One mode of oscillation (only observable at 4 and 6 torr), has the property that the frequency decreases with a decrease in pressure, a decrease in DC current and a constant DC voltage.

d) The second mode of oscillation, occurring at lower DC current values than the previous described mode, has a characteristic nose form when the DC current is plotted versus frequency (figure 3.27). Starting out at the high current side, a high frequency is observed. Initially the frequency decreases with decreasing current. At a particular current, I_N, a minimum frequency is obtained. Decreasing the current further will increase the frequency. This



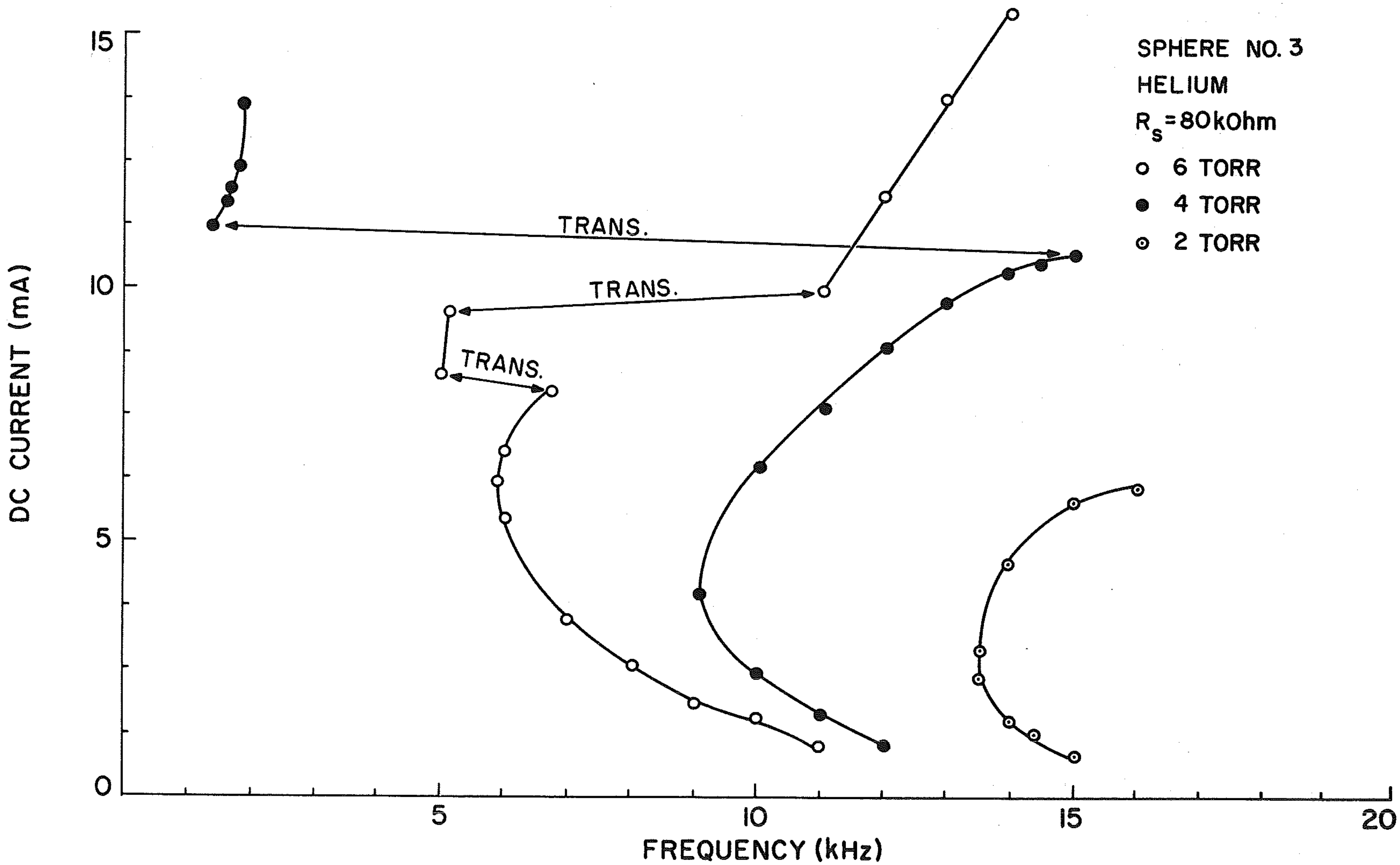
DC Discharge Characteristic

FIGURE 3.25



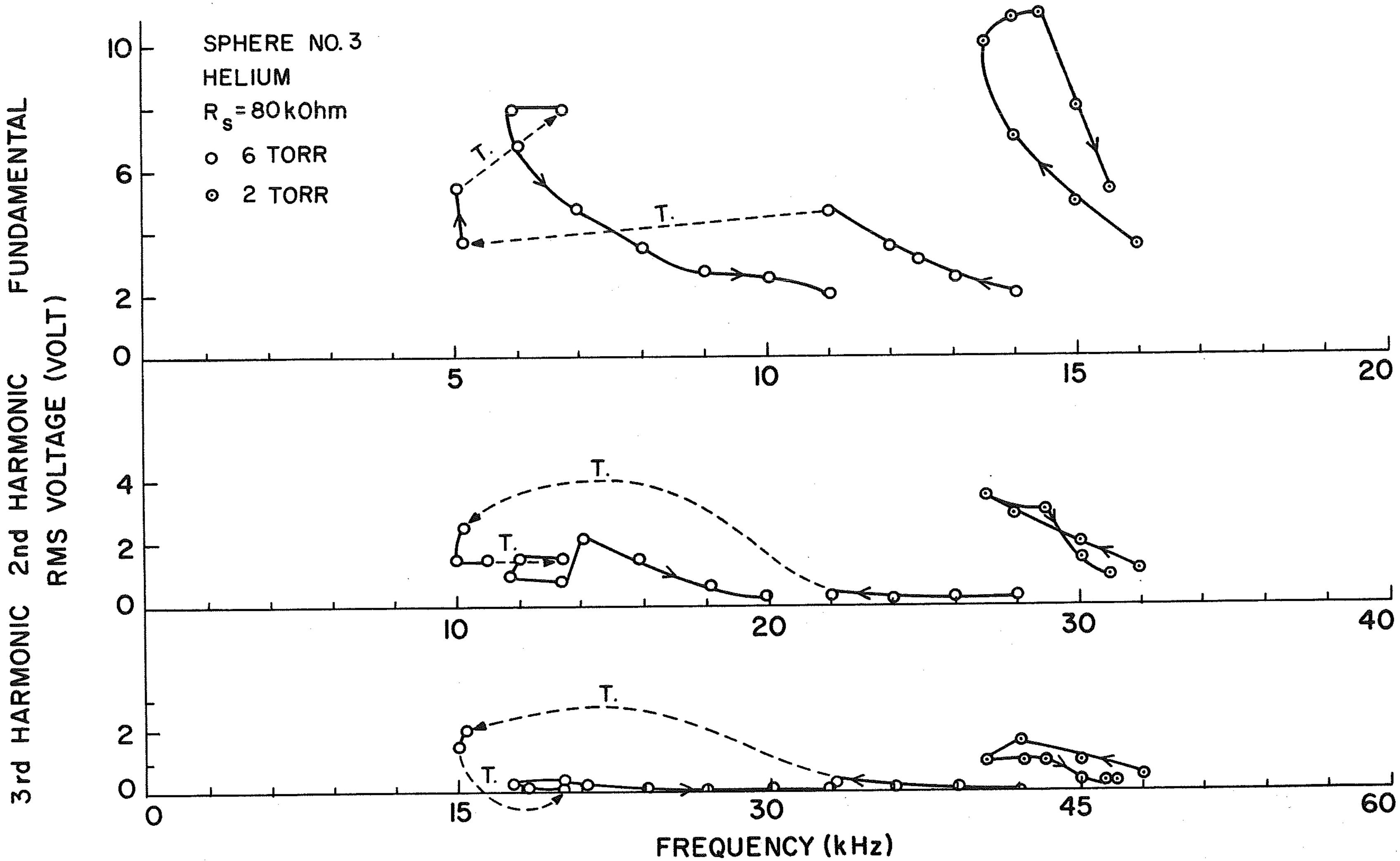
DC Voltage vs Frequency

FIGURE 3.26



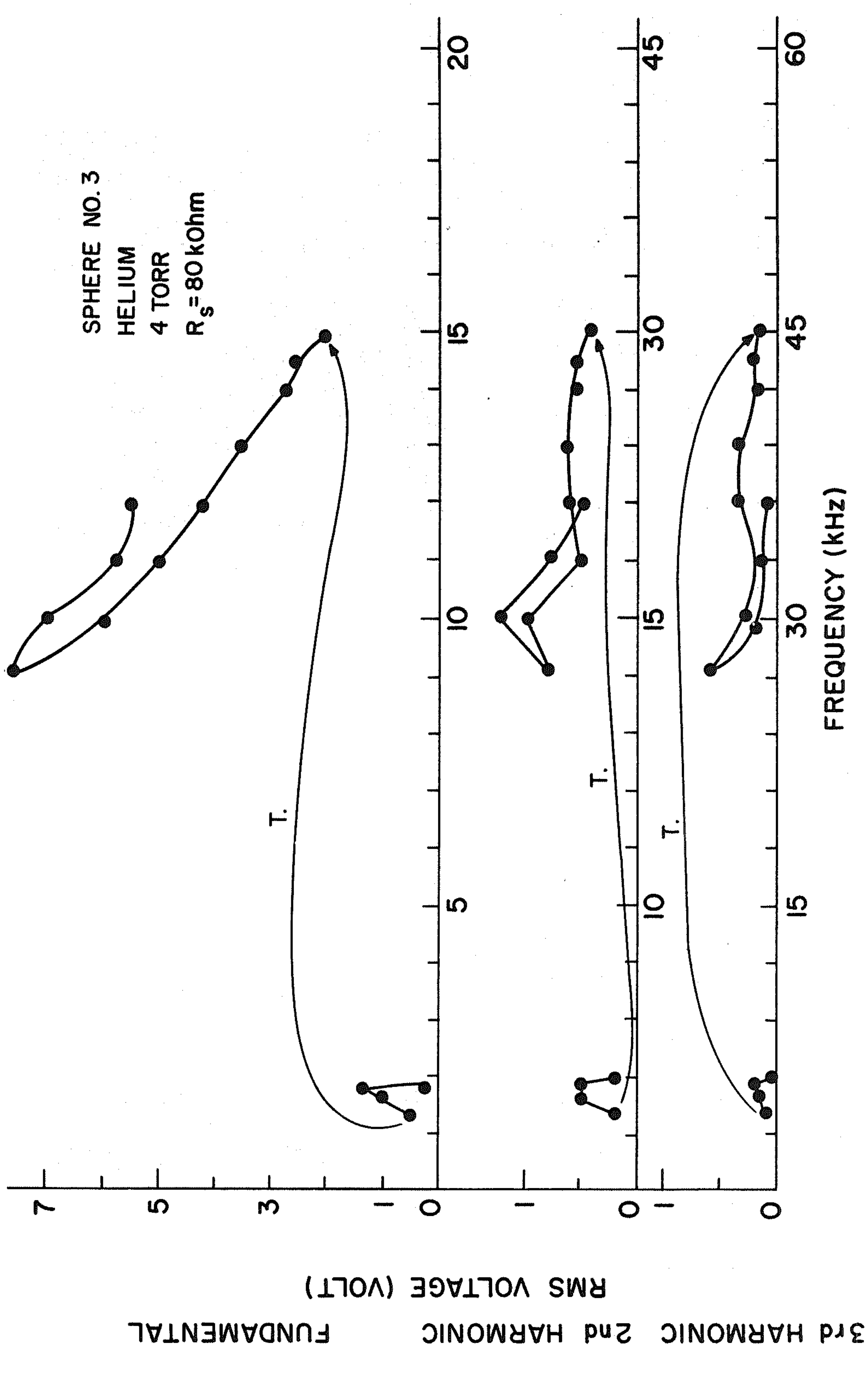
DC Current vs Frequency

FIGURE 3.27



Magnitude of the Fundamental, 2nd and 3rd Harmonic vs Frequency

FIGURE 3.28



Magnitude of the Fundamental, 2nd and 3rd Harmonic vs Frequency

FIGURE 3.29

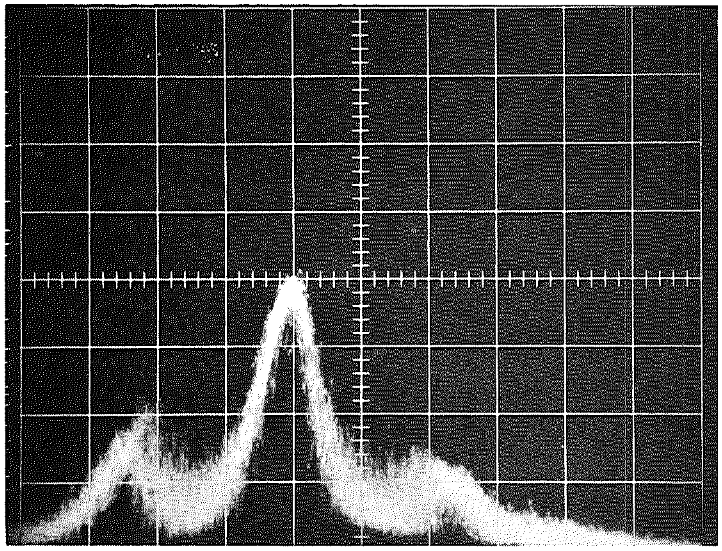
negative slope portion of the curve is similar to those found for nitrogen and argon. The nose curves are shifted with increasing pressure toward lower frequencies.

e) At 6 torr, a third mode of oscillation is observed in between the two previous described modes.

f) At 4 torr, an overlapping of the two modes occurs. Modulation of the second mode by the first mode is noticed during the transition as shown in figure 3.30. The 15 kHz oscillations are modulated by the lower frequency mode which occurs at the same time. The first mode is quenched and the modulation disappears by decreasing the current.

3.1.6 Effect of the Diameter of the Cathode Upon the Plasma Oscillations

In order to determine the effect of the magnitude of the diameter of the cathode on the plasma oscillation, sphere no. 6 which has a magnetic field comparable to the field of sphere no. 3 was used. The data obtained for this sphere has been plotted in figures 3.31, 3.32 and 3.33. Two pressures (1 and 2 torr) have been studied. Comparison with the data obtained for sphere no. 3 as represented in figures 3.2 to 3.6 and 3.11 to 3.15 indicates two distinct differences. First for a fixed pressure the frequency range for the larger sphere is shifted toward lower values. Second the magnitude of the fundamental of the plasma oscillation for the larger sphere is always smaller than the magnitude of the second harmonic. The value of R_s has not been specified in the figures 3.31 to 3.33 because various values were used. The

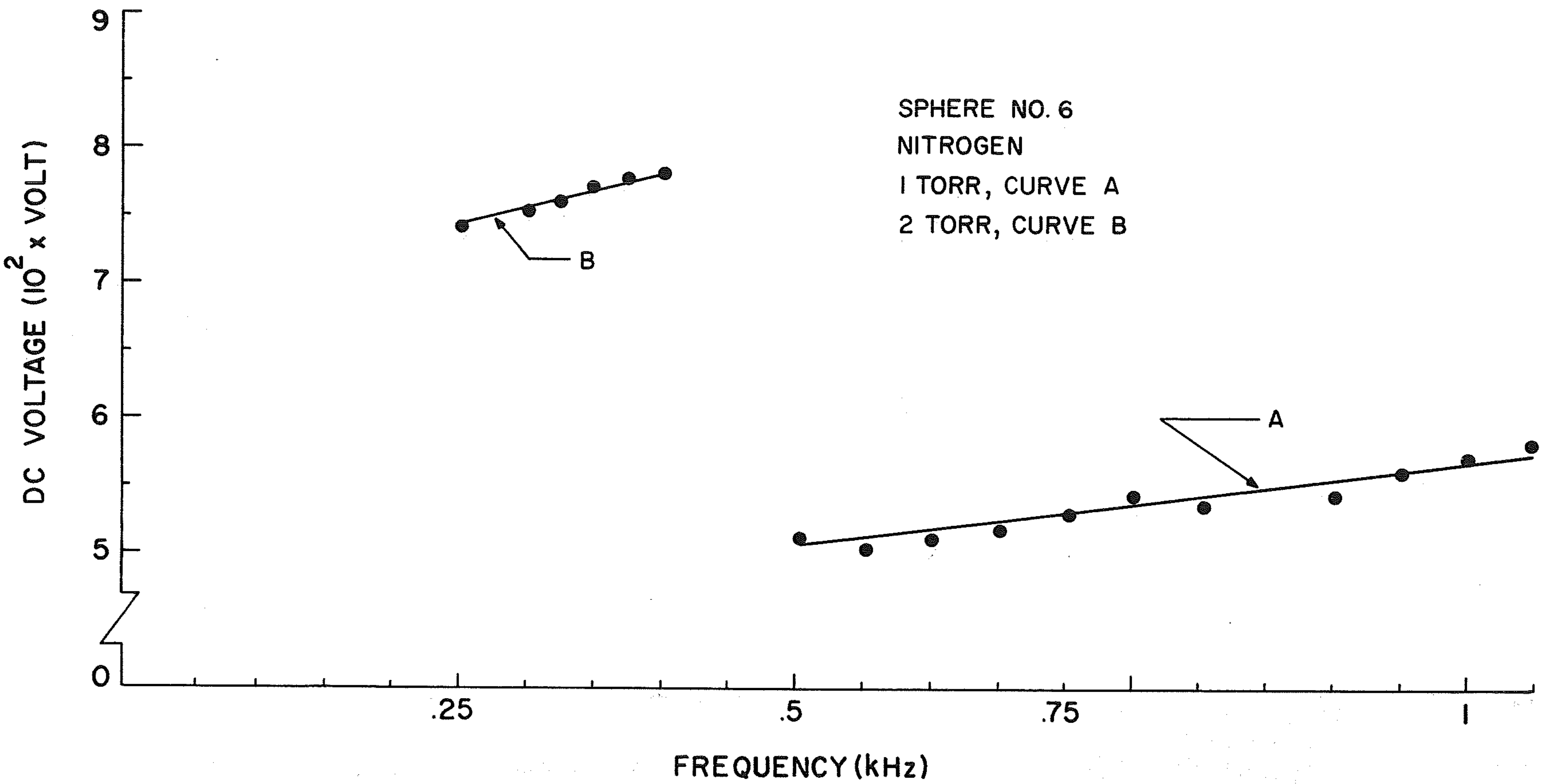


Horizontal scale, 0.5 kHz /div.
Vertical scale, 0.5 rms Volt /div.
V_{DC} = 260 Volt, I_{DC} = 10.8 mA,
Sphere No. 3, 4 Torr.

The second pulse is the 15 kHz carrier, role played by the second mode oscillations. The first and third pulses correspond to the 2 side-bands due to the 1.4 kHz first mode oscillations.

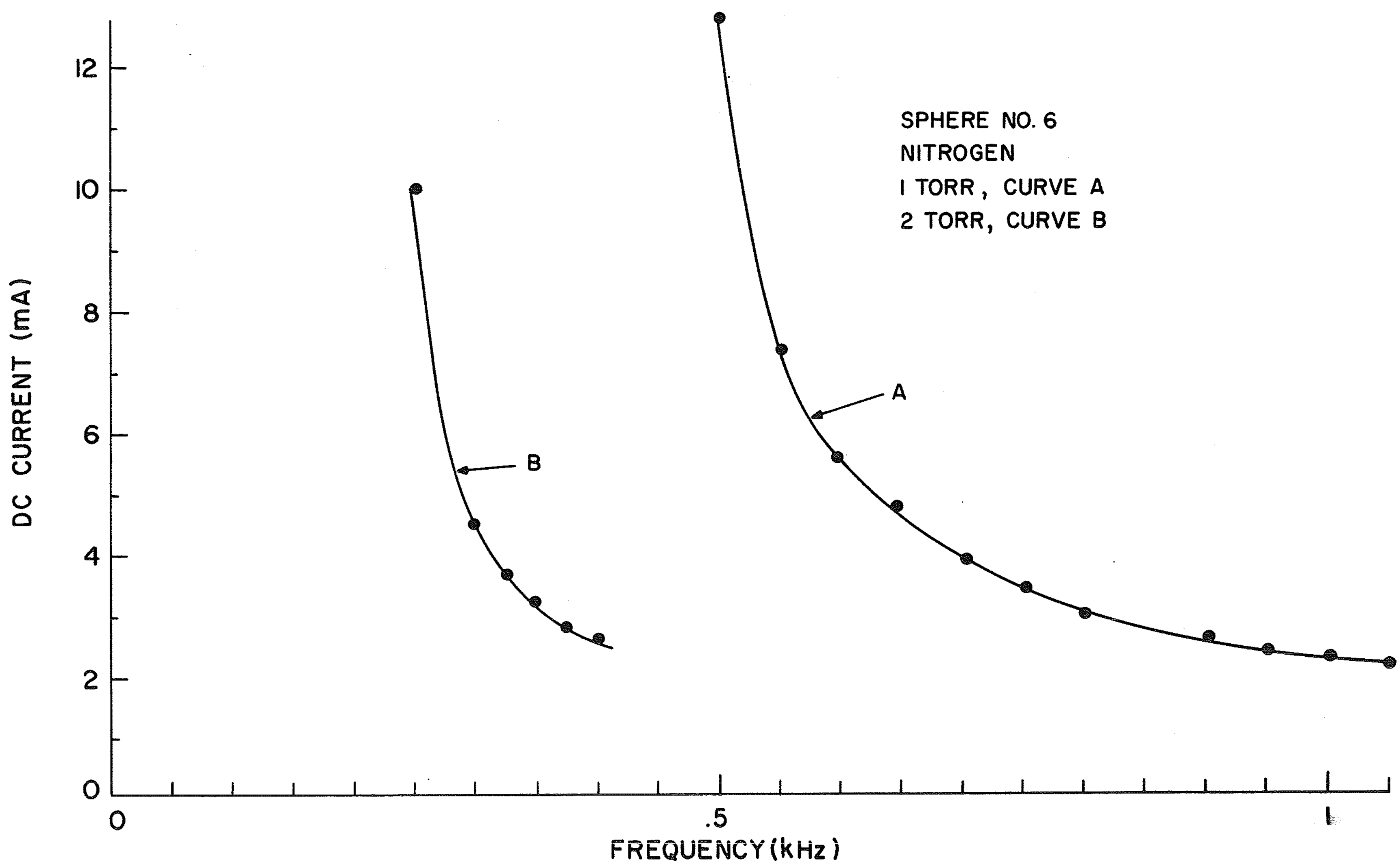
Internal Modulation of Modes in Helium Plasma
Transition Region

FIGURE 3.30

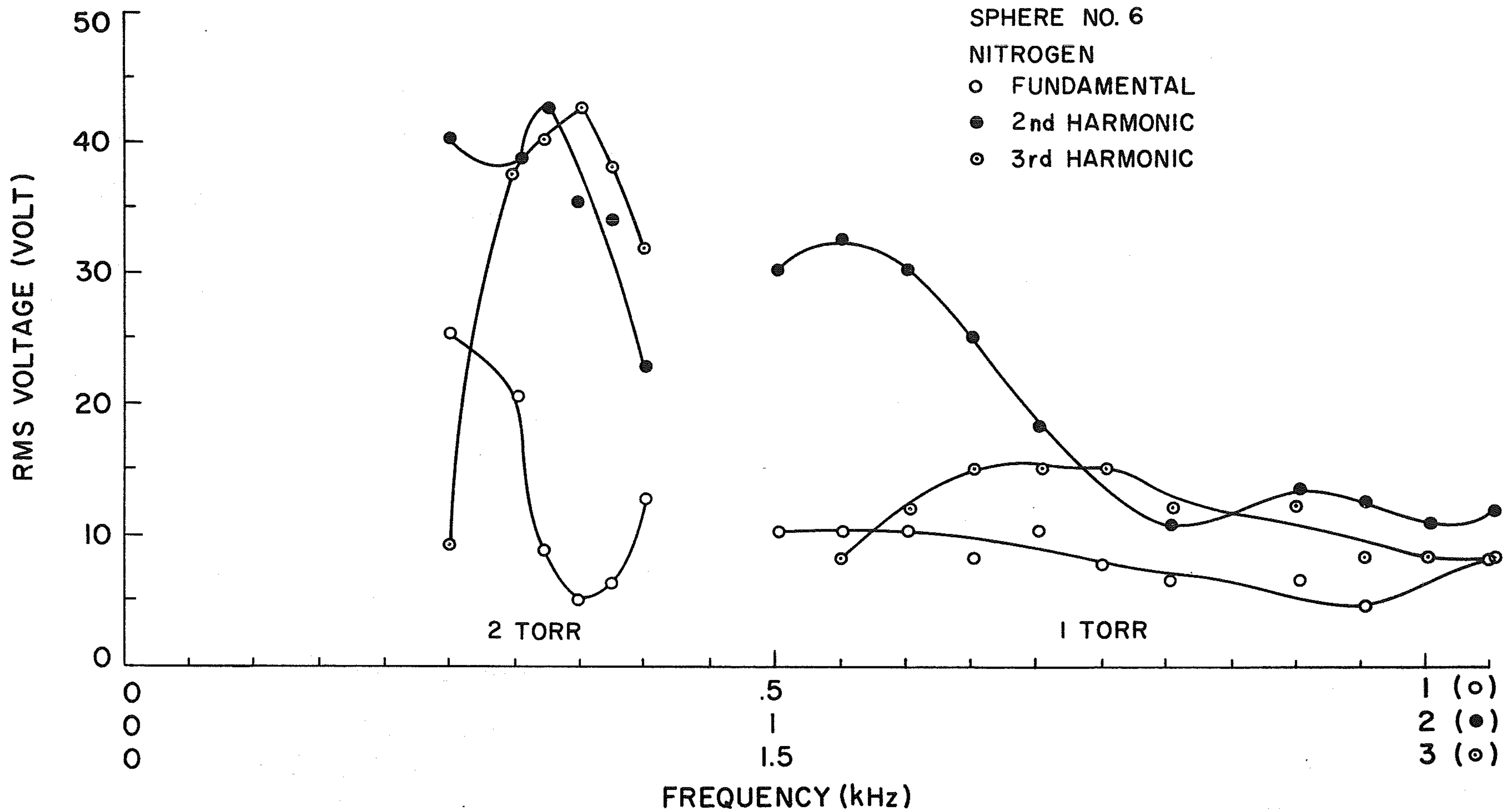


DC Voltage vs Frequency

FIGURE 3.31



DC Current vs Frequency
FIGURE 3.32



Fundamental, 2nd Harmonic and 3rd Harmonic vs Frequency

FIGURE 3.33

high current points are obtained with R_s = 80 kohm. The low current points with R_s = 228 kohm. R_s = 160 kohm is used for the points in between. In the overlapping regions of two resistor values no difference is noticed due to the different resistor values. The end points of the curves are obtained just before the bulk of the plasma starts pulsating and quenches.

Sphere no. 5 has a magnetic field which is an order of magnitude less than the fields of the previously used cathodes. In addition its surface is polished while the surfaces of the other spheres are rough. For these reasons comparison is difficult. However, it was observed that the belt formed was very broad with only the pole caps uncovered. This condition is intermediate between the zero field and strong field spheres.

Unfortunately no small sphere with a field strength in the neighborhood of sphere no. 3 having unpolished surface is available to better illustrate the effect of diameter upon the plasma oscillations.

Briefly, we can say that for comparable field strengths spheres with larger diameter give rise to plasma oscillations with lower fundamental frequency at same DC current values.

3.2 Two Terminal Characteristic with Constant Frequency

In examining the constant frequency charactertistic, four values of frequency were chosen arbitrarily i.e., 0.5, 1, 2 and 4 kHz. The measured quantities were V_{DC}, I_{DC}, the magnitude of the fundamental, 2nd and 3rd harmonic (rms volt), pressure and the frequency. Sphere no. 3, nitrogen as a residual gas, and R_s = 80 kohm are used in all the obtained data. The data present typical measured curves.

Figure 3.34 shows the DC discharge characteristic for constant frequency. It is noticed that the characteristics are shifted down and toward the left for increasing frequency.

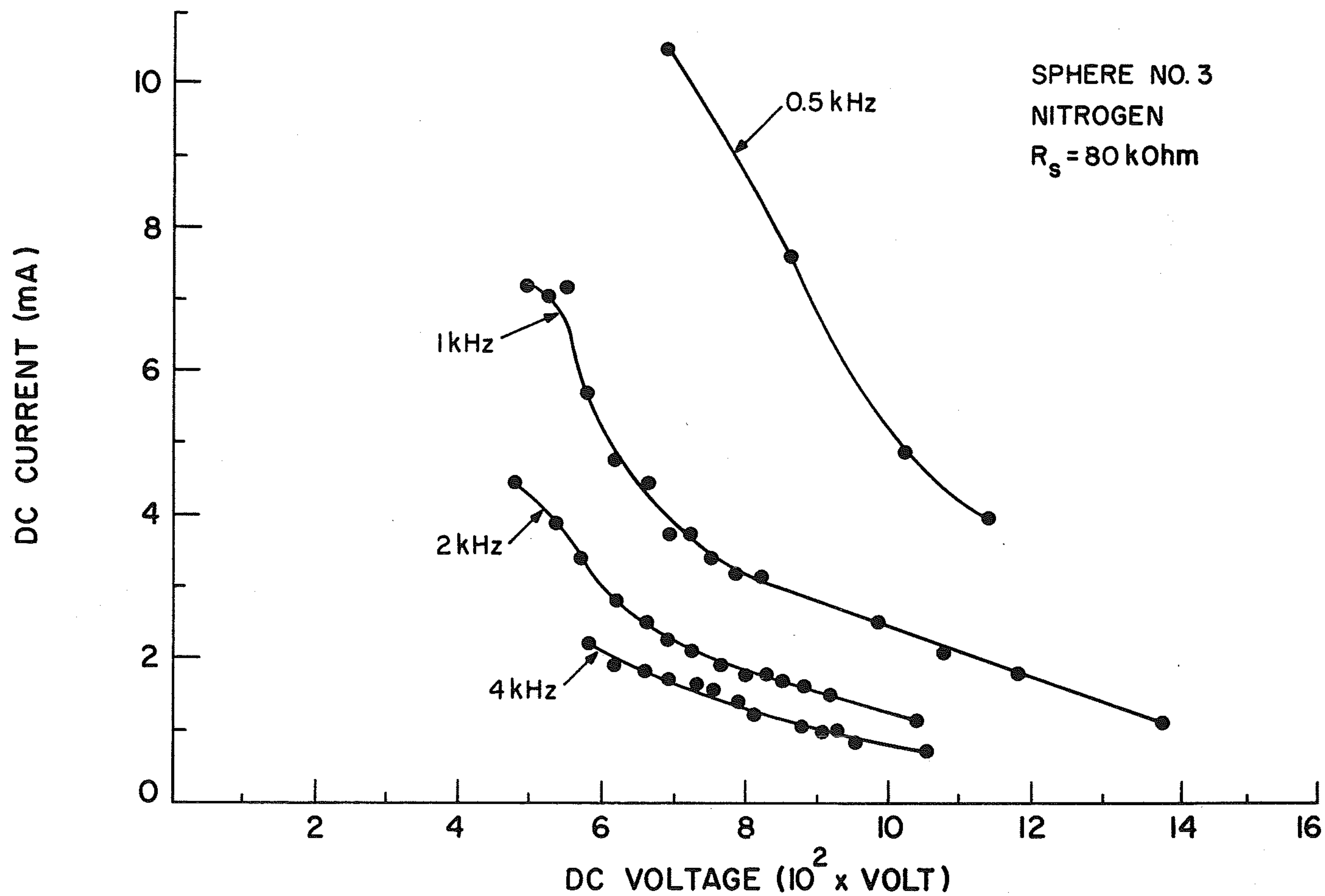
Figures 3.35 and 3.36 give the DC voltage and DC current versus pressure. The curves of 4 and 2 kHz have the end points at 2.5 torr because at pressures larger than 2.5 torr the plasma quenches. The end point of the 0.5 kHz curve corresponds to the limit of the DC power supply. At this point the plasma still exists but a higher voltage than was available is necessary to decrease the frequency further. From these figures one observes that the high frequency limit decreases with increasing pressure. Further as we have seen previously it is observed that for a fixed pressure the highest frequency plasma oscillation occurs for highest voltage and lowest current values.

In figure 3.37 and 3.38 the amplitudes of the fundamental, 2nd and 3rd harmonic versus pressure are depicted. The fundamental possesses a characteristic minimum which for increasing frequency is shifted toward lower pressures. For the 4 kHz, the minimum was not observed. For the 2, 1 and 0.5 kHz curves the minimum occurs respectively in the neighborhood of 1.1, 1.7 and 3 torr respectively.

3.3 Mixing

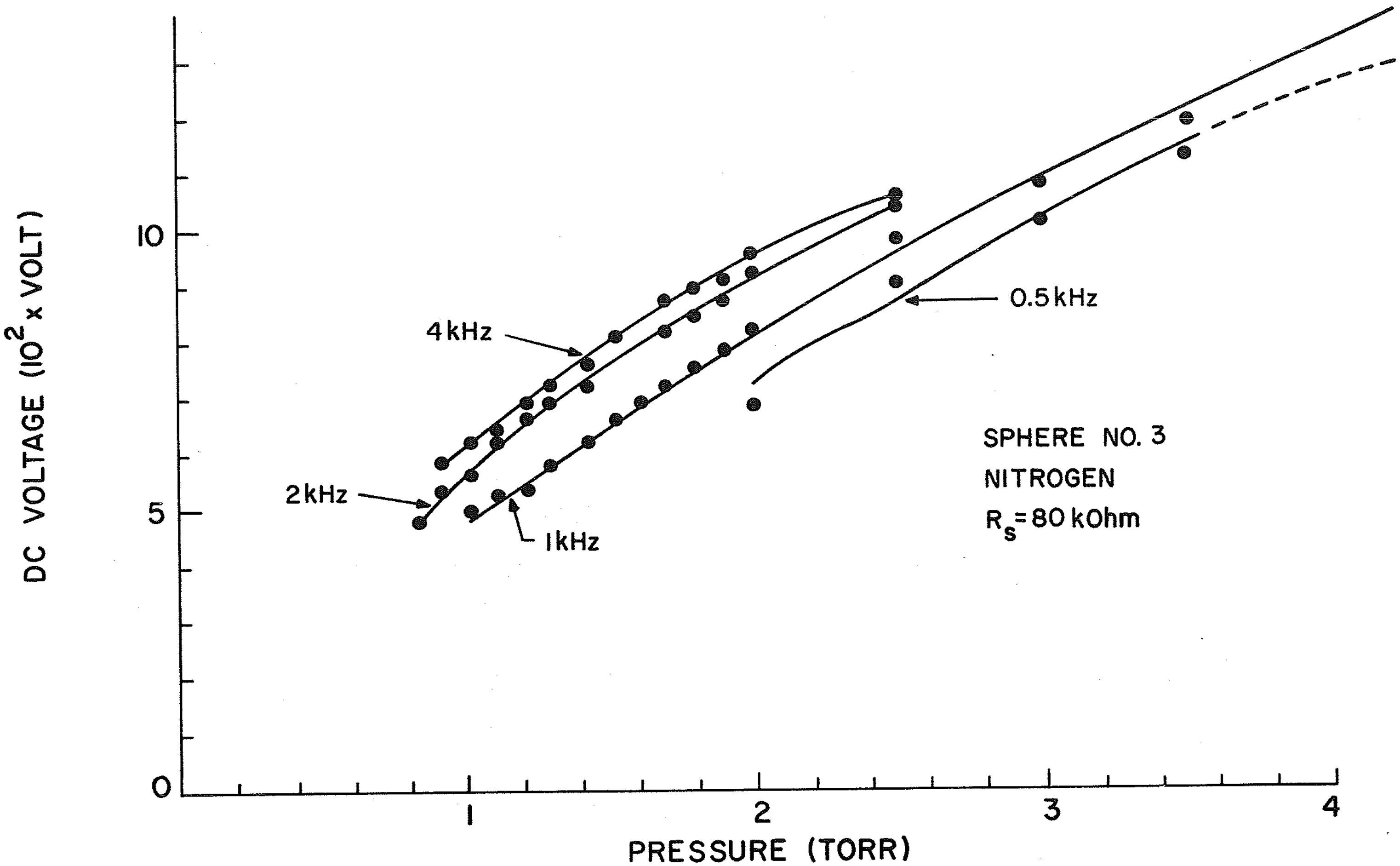
A completely different phenomenon is observed by modifying the apparatus as shown in figure 3.39.

The basic discharge circuit is the same but the detection device is now a wire wound around the bell jar (15 turns) which is connected to a Tektronix storage oscilloscope type 564, equipped with time base type 2B67 and spectrum wave analyzer type 3L.5.



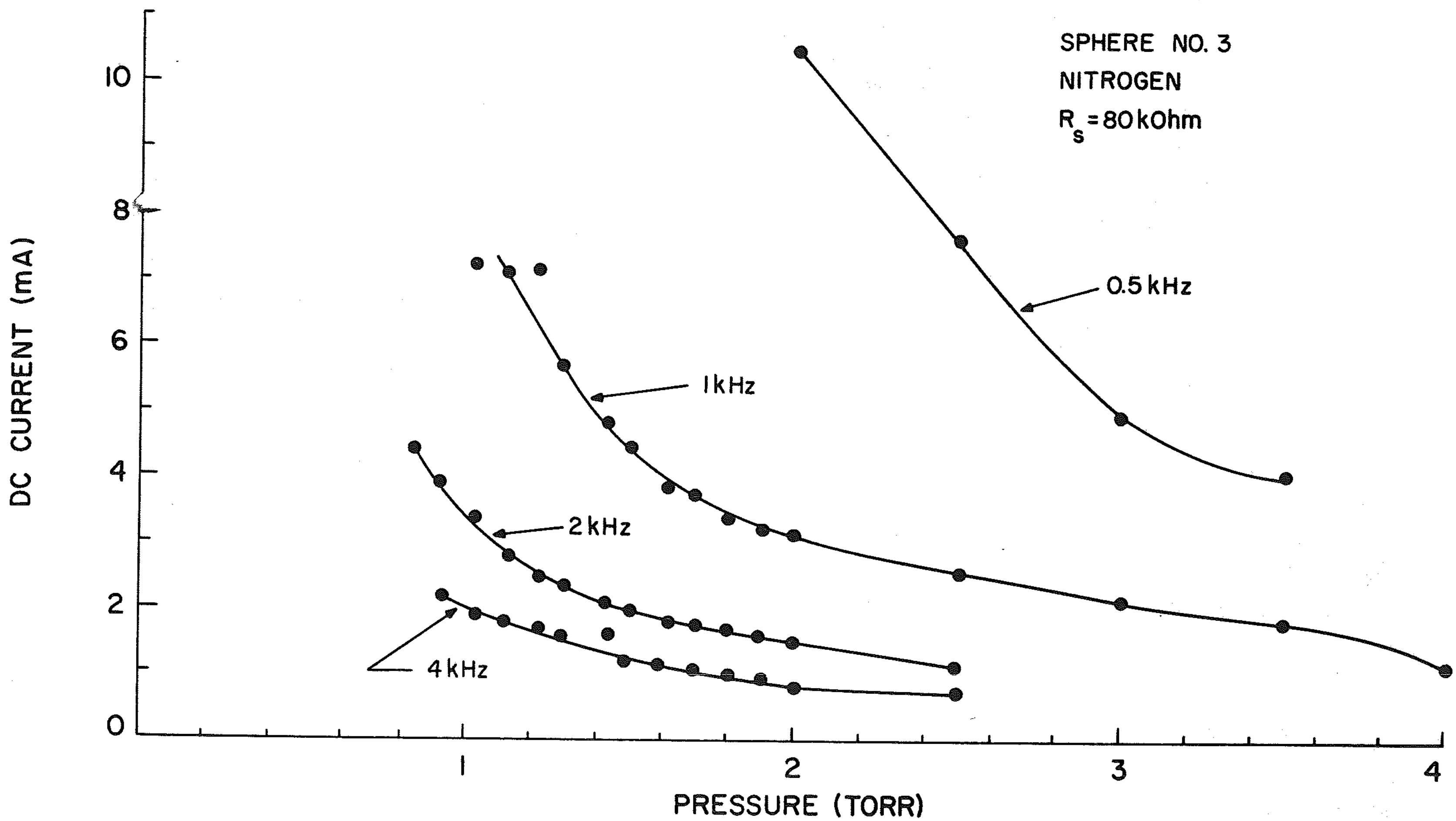
DC Discharge Characteristic for Constant Frequency

FIGURE 3.34



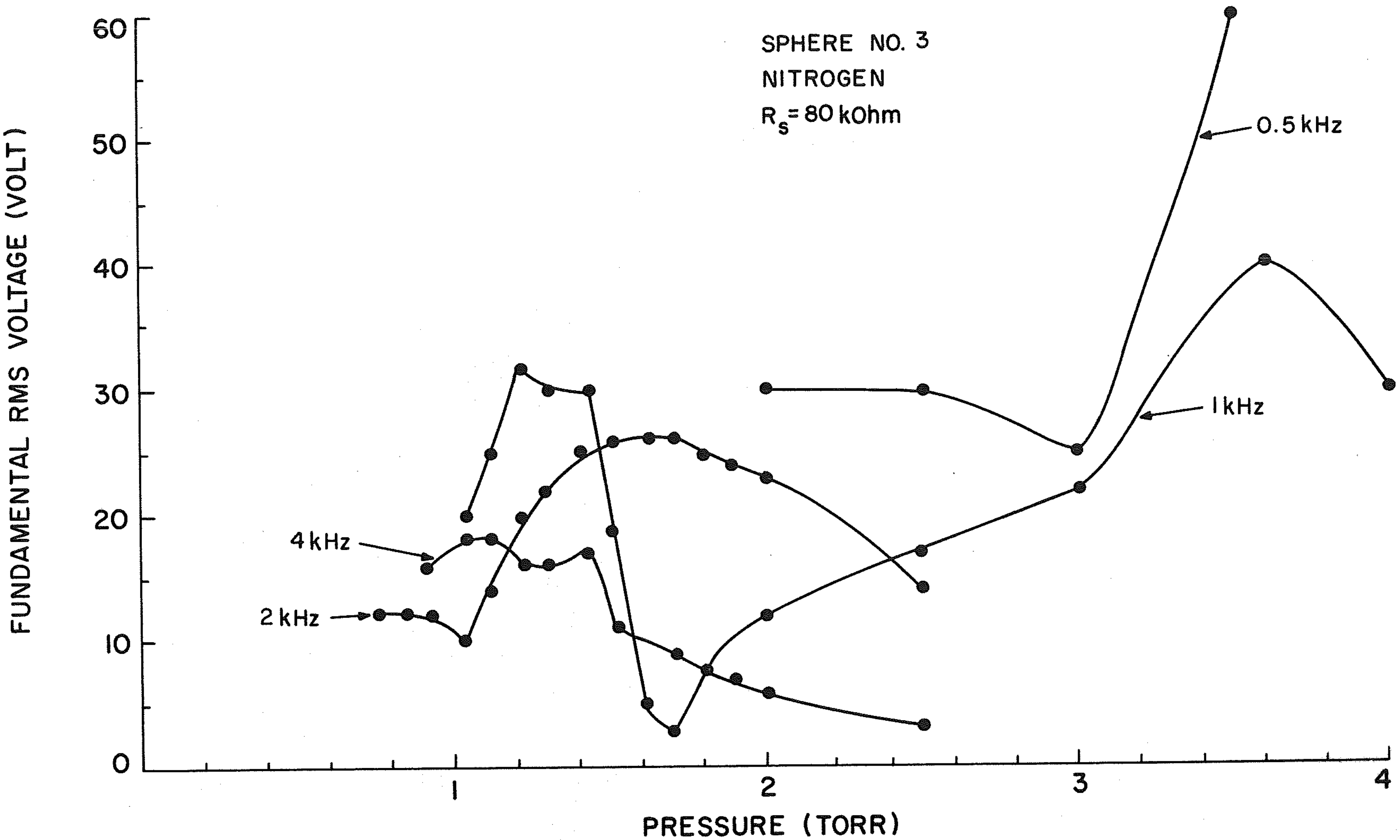
Pressure vs DC Voltage

FIGURE 3.35



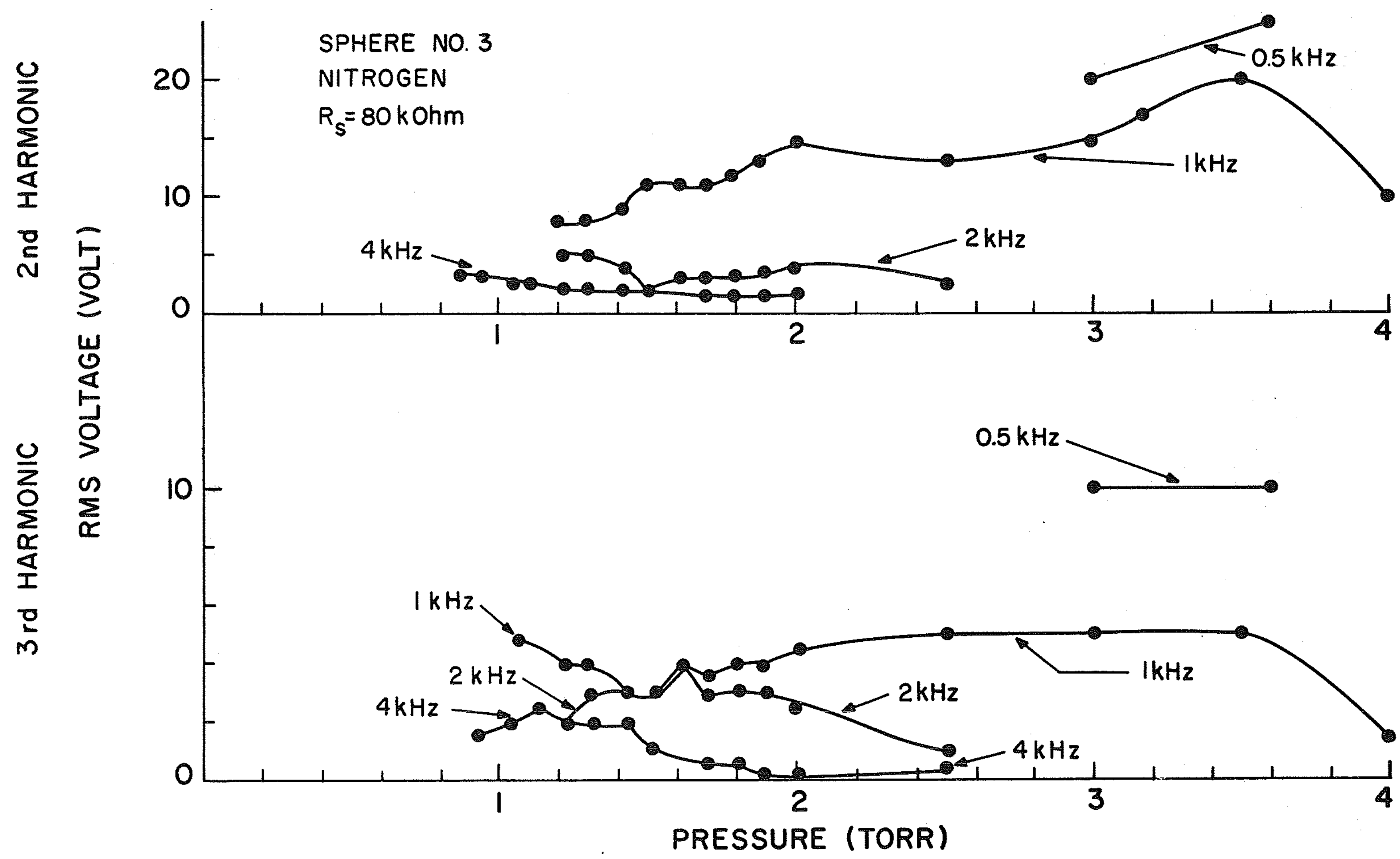
Pressure vs DC Current

FIGURE 3.36



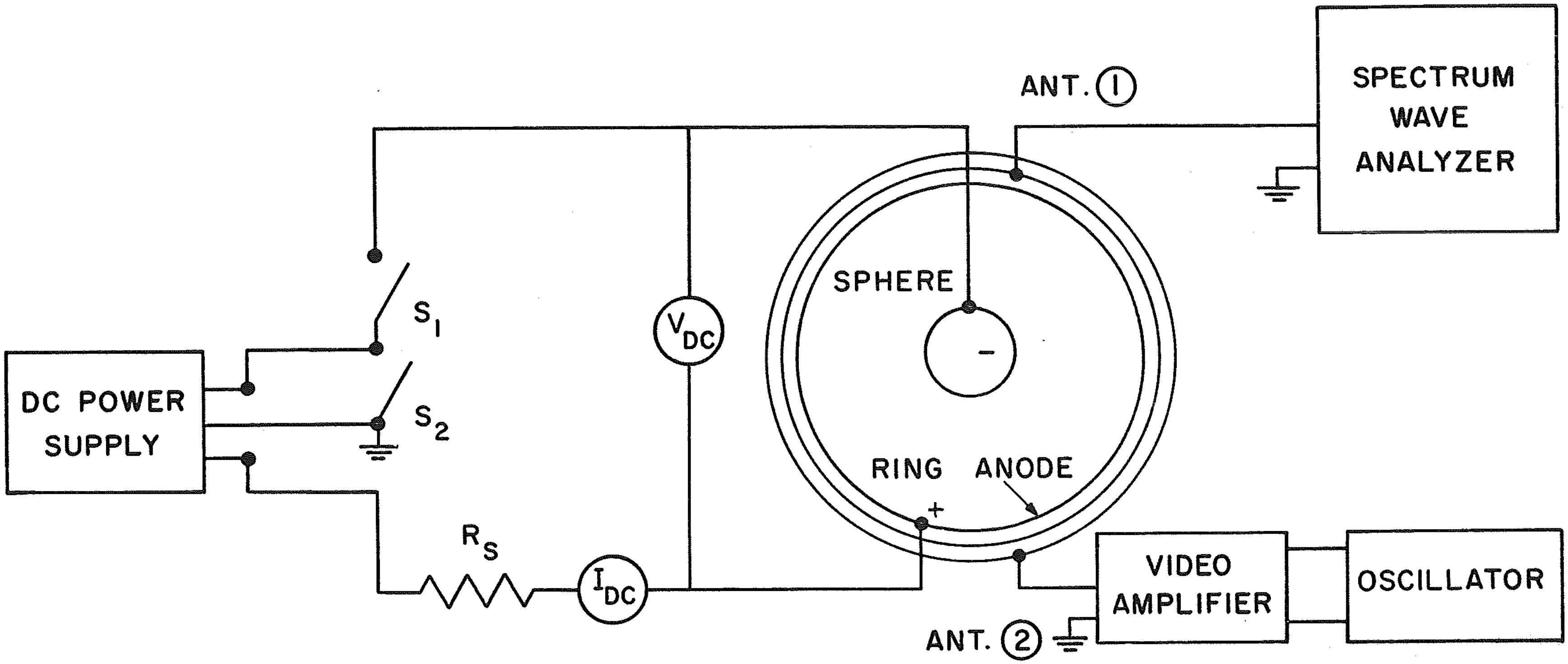
Fundamental vs Pressure

FIGURE 3.37



2nd and 3rd Harmonic vs Pressure

FIGURE 3.38



Schematic for the Mixing Experiment

FIGURE 3.39

A second wire antenna (30 turns) is wound around the belljar connected to the output of a hp amplifier model 450A whose input is connected to a hp wideband oscillator model 200 CD.

In this experiment, sphere no. 3, R_s = 160 kohm, and nitrogen as a residual gas are used. Further keeping the pressure constant at 1 torr, the DC power supply conditions are set to obtain a particular frequency e.g. 8 kHz. This signal with its harmonics is observed by means of the spectrum wave analyzer.

Antenna (1) also detects the signal from the hp oscillator, whose volume is adjusted to eliminate harmonics.

If the external oscillator is at 7 kHz then at antenna (1) both signals i.e. from the plasma and the external oscillator are observed. In addition a third signal at 1 kHz with its harmonics is noticed. This difference signal can be varied in frequency by either changing the external signal frequency or by changing the frequency of the plasma oscillation.

Shifting the frequency of the external oscillator it is noticed that mixing occurs not only with the fundamental but also with the 2nd and 3rd harmonic of the plasma oscillation.

Thus one may consider the plasma oscillations as a generator and the plasma itself as the non-linear medium necessary to obtain the mixing effect.

4. CONCLUSIONS

Plasma oscillations are found in a cold cathode discharge where the cathode is a magnetized sphere.

The frequency of the plasma oscillations has the following characteristics:

1. Under a constant pressure of either nitrogen or argon, the frequency increases with decreasing current and increasing voltage. For helium, exceptions have been observed.
2. The frequency increases with decreasing pressure for nitrogen, argon and at low current values also for helium. A high current mode with helium as the residual gas shows opposite behavior.
3. The frequency is independent of the external circuit series resistance.
4. The frequency is independent of the magnetic field within experimental error.
5. The frequency decreases with increase in the diameter of the sphere.
6. The frequency range for nitrogen and argon plasmas are approximately the same. Nevertheless argon plasmas have a lower frequency limit which can be extended to 0 Hz. Under certain discharge conditions it has been noticed that an argon plasma dot revolves in the equatorial plane. The number of revolutions per minute is governed by the setting of the DC power supply. Helium plasma shows much higher frequency oscillations.

Comparing the frequencies of the oscillations for the three gases at a particular current just before the plasma quenches e. g. 0.65 mA, one has the following frequencies: $F_{N_2} = 5.\text{kHz}$, $F_A = 4.\text{kHz}$, $F_{He} = 15\text{kHz}$. It is seen thus that in the low current limit before the plasma quenches, the ratio of the frequencies is approximately equal to the root of the inverse ratio of the ion masses:

e. g. and

$$\frac{F_{N_2}}{F_A} = 1.25 \qquad \frac{F_{He}}{F_{N_2}} = 3$$

$$\sqrt{\frac{M_A}{M_{N_2}}} \approx 1.20 \qquad \sqrt{\frac{M_{N_2}}{M_{He}}} \simeq 2.65$$

The magnitude of the plasma oscillations has the following characteristics:

1. Under constant pressure, the largest oscillations are found at the low frequency side which is characterized by minima and maxima and is the high current and low voltage region.
2. The magnitude of the oscillations is a function of pressure.
3. An increase in the resistor R_s has a mixed effect upon the magnitude of the plasma oscillations. At low frequency the oscillations are damped, at medium frequency the oscillations increase in magnitude, and at high frequency the magnitude of the plasma oscillations is unaffected by the change in resistance.

4. The effect of magnetic field and ion mass upon the magnitude of the oscillations has not been determined due to experimental limitations.

5. Increasing the diameter of the sphere causes a suppression of the fundamental and an enhancement of the second and third harmonic.

An empirical expression relating frequency with pressure, current and voltage has been determined in the following way for the nitrogen plasma: From figures 3.2 and 3.3, and 3.8 and 3.9, it is possible to calculate the DC resistance defined as the ratio of the DC voltage to DC current. In figure 4.1, the frequency versus DC resistance is plotted for a pressure of 1 and 2 Torr. Also the obtained curves can for a large part be approximated by a straight line passing through the origin. From the above plot, it is easily seen that for

curve (a) $f = A_2 R_{DC}$

and for curve (b) $f = A_1 R_{DC}$

where f = frequency

R_{DC} = DC resistance

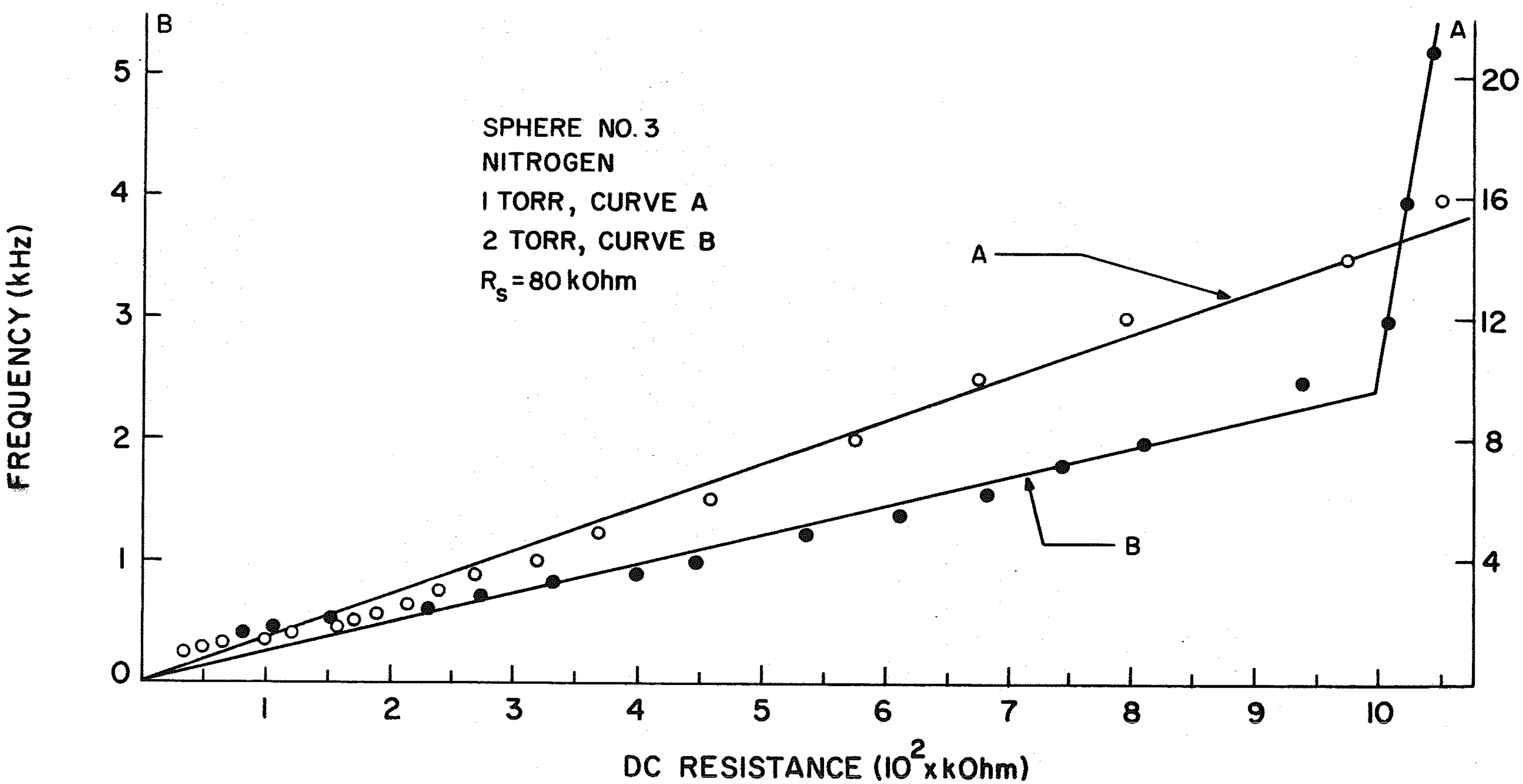
$A_2 = \frac{1}{400} \frac{Hz}{ohm}$ constant pressure of 2 Torr

$A_1 = \frac{14}{975} \frac{Hz}{ohm}$ constant pressure of 1 Torr

In general we can write that

$$f = A(p) R_{DC}$$

where $A(p)$ is a constant dependent upon the pressure p and $R_{DC} = \frac{V_{DC}}{I_{DC}}$.

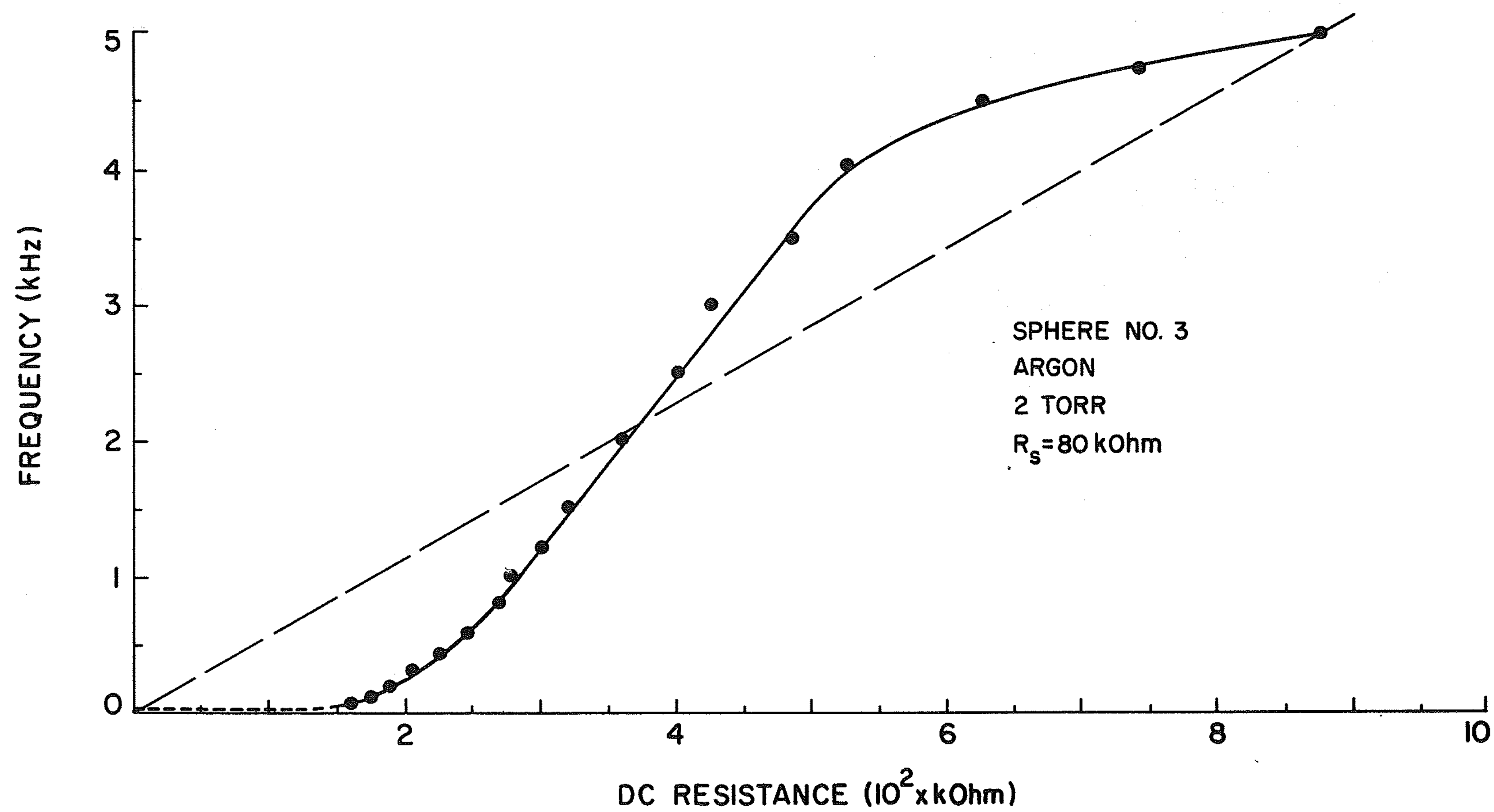


Frequency vs DC Resistance

FIGURE 4.1

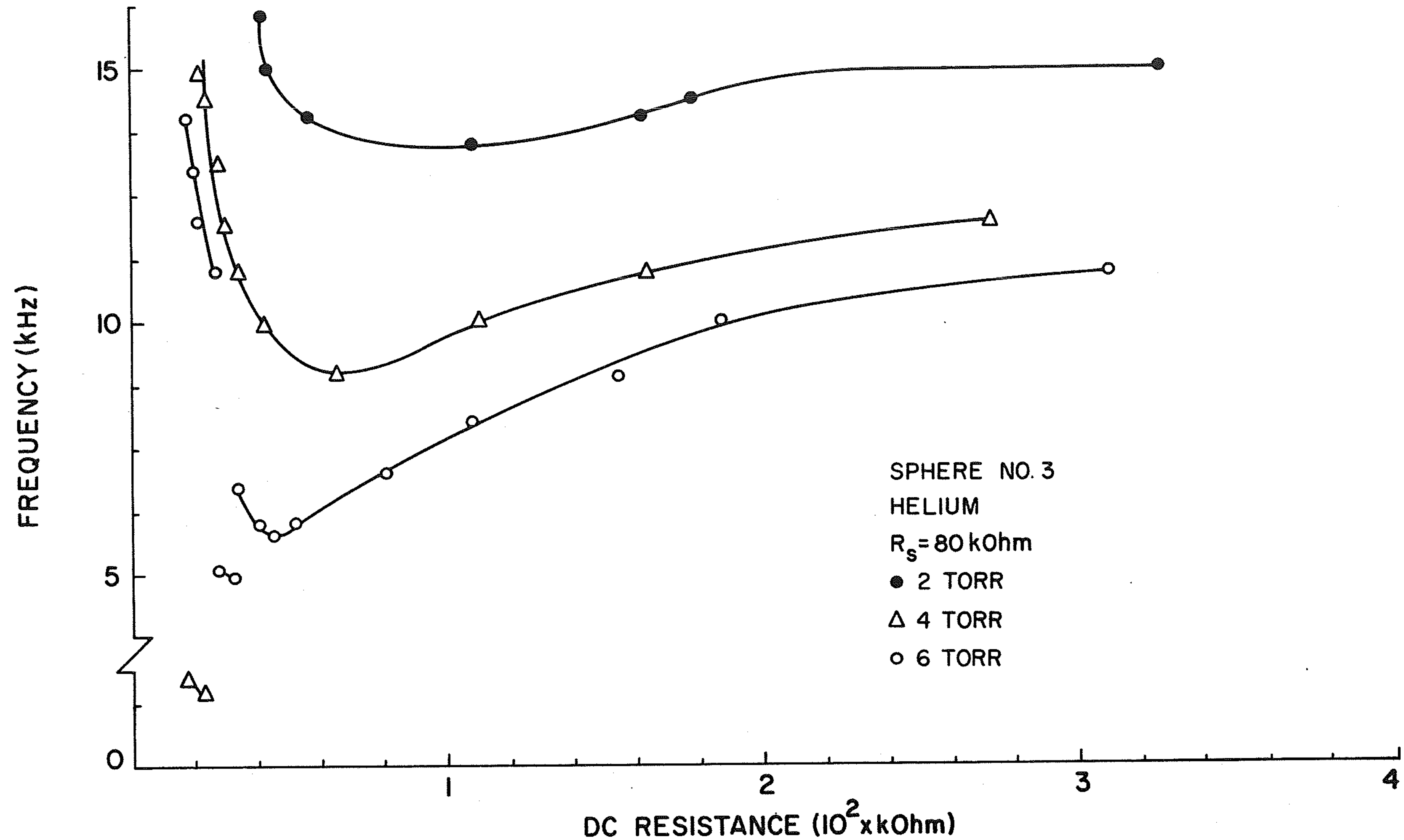
Applying the above method for the argon and helium plasmas one gets frequency versus DC resistance plots, as shown in Figures 4.2 and 4.3 respectively. It is seen that for argon, one can still write a formula of the form $f = A(p)\, R_{DC}$, but the actual curve deviates much more from the straight line approximation as in the case of the nitrogen plasma. The approximation breaks completely down for the helium gas.

At the present time it is not clear what type of plasma oscillations are giving rise to the numerous phenomena observed thus far. Various mechanisms are presently under investigation as well as further experimental investigations including a study of the effects of sphere rotation and the spatial characteristics of the oscillations. However, it should be noted that this phenomena could be used as the basis for a highly sensitive pressure gauge or controller in a pressure range where the normal gauges are relatively insensitive. This is especially true in the low current portion of the characteristics where a change in pressure of a few tenths of a torr will cause a change in frequency of a few thousand Herz.



Frequency vs DC Resistance

FIGURE 4.2



Frequency vs DC Resistance

FIGURE 4.3

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