INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

RESEARCH REPORT

NAGOYA, JAPAN

Resonance Probe Characteristic

in a Non Uniform Plasma

G. Lampis*, S. Aihara and K. Takayama

IPPJ-77 November 1968

Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya, JAPAN.

* Research Fellow of the Japanese Society for the Promotion of Science.

Abstract

The effect of a non-uniform density distribution in a plasma, on the transmission of r.f. power across it, is studied experimentally. It is found that the r.f. transmission characteristic presents double resonance, when the geometry of the transmission and the density distribution, within the plasma, allow the r.f. electric field to resonate in parallel with two different regions of plasma, having different densities.

§ 1. Introduction

Anomalous radio frequency characteristics presenting multiple peak structure, were previously observed (1,2,3,4). The purpose of this experiment is to study the behavior of the multiple r.f. resonances in a non uniform plasma, where the density distribution is known, by using different geometries.

§ 2. Description of the Plasma Parameters

A low density non uniform plasma is produced in a metal vessel (TPQ metal machine) (Fig.1), by a back diffusion type source (5,6); the gas used is He at a pressure of 1.3×10^{-3} torr; the potential of the grid G_1, which can be varied up to +155 volt, determines the acceleration voltage of the ions coming from the source; the potential of the grid G_2 is used for controlling the discharge, and is generally kept at +70 volt; the anode voltage is kept at +500 volt. The ion beam coming from the source spreads out with a divergence of about 8°, as confirmed by Faraday cage measurements in the radial direction.

The plasma density distribution, within the machine, measured by the Langmuir probe method, presents an exponential decay (6) in the axial direction, due to ion-neutral collisions and to the radial spreading of the ion beam. The e fold longitudinal decay length is 17cm, for the high acceleration voltage case and 19.5cm for the low voltage case. In the transversal direction, the density profile, measured at the distance of 13cm from the cathode, where the radial probes are located, decays to the sides with a double exponential behavior. Fig(2) shows two typical profiles for the two different cases of high and low acceleration voltages ($P = 1.3 \times 10^{-3}$ torr.). The e fold decay lengths of the profiles are not sensibly changed from one case to the other; the decay length of the internal profile near the axis of the machine is about 13 ~ 14cm; for the external profile near the walls the length is 17 ~ 18cm. In the high acceleration voltage case, the maximum density, in the plane where the radial electrodes are located, is 10^6 el/cc, on the top of the profile, and 2.5×10^5 el/cc on the external wings at a distance of 20cm from the center, while for the low acceleration case the same values are 4×10^5 el/cc and 1.5×10^5 el/cc. For the low density case the top of the density profile is flat up to a radius of 3.5cm. Fig(3) shows how the position of the elbow, connecting the two exponentials, changes with the acceleration voltage.

The temperature of the electrons is constant all across the space within the metal vessel and is about 0.3 ev. This value does not sensibly vary with the acceleration voltage of the ions from the source.

§ 3. Radio Frequency Transmission Measurements

An oscillator whose frequency can be varied from 50 Kc/s to 10Mc/s, and whose output voltage is kept at 2.5 volt r.m.s. injects r.f. current in the plasma, through a movable plane radial electrode having a diameter of 60mm (Fig.1). The r.f. current, transmitted across the plasma is received by a second radial electrode and is fed to a 50Ω load; the output voltage is measured by a vacuum tube voltmeter. The same detection can be done too on an axial movable probe; during the r.f. measurements, all the electrodes are kept floating.

The shape of the r.f. characteristic is measured both in the transversal and in the axial direction, always transmitting the r.f. power from the same radial electrode.

The radial r.f. transmission characteristic, that is the admittance of the sheath plasma system between the radial electrodes, presents two distinct resonance peaks in the case of high acceleration voltages (90v ~ 150v), while, for low acceleration voltages (~30v), only one resonance is found (Fig.4); for intermediate situations the characteristic presents one peak together with one shoulder. The radial r.f. characteristic was measured for different distances between the transmitting and the receiving electrodes. The frequency of the two peaks and of the two minima, in the double resonance case depends on the distance between the electrodes as shown in Fig(5.1). The amplitude of the two peaks decays with the distance between the probes as shown in Fig(5.2); for small distances ($D < 10$cm), the low frequency peak disappears, while for large distances ($D > 30$cm) the same effect happens for the high frequency one. In the case of low acceleration voltage, (low density case) when the characteristics presents only one peak, the positions of the "peak" frequency and of the "minimum" frequency, versus the distance between the radial electrode are shown in Fig(6.1). The amplitude of the peak decays with the distance between the electrodes as shown in Fig(6.2). For growing values of the acceleration voltage, the peak structure changes from single to double resonance, for a fixed distance between the radial electrodes. Fig.7 shows, for a different run of data, how the single resonance of the low density case, is transformed into the double resonance of the high density case, for a fixed distance of 25cm between the radial probes.

§ 4. Model

For interpreting the results presented in Figs 4,5,6,7 for the high density case, the following model is used (see Fig 8.1 and 8.2).

The resonance characteristics can be considered as the superposition of two different resonances, the first (low frequency) is the sheath resonance with the low density plasma of the density profile tail away axially from the plane where the probes are; this resonance feels slightly also the relatively low density wings in the radial direction, when the distance between the electrodes is large. This resonance does not in consequence vary appreciably its frequency position when the probes are moved away, as seen in Fig 5.1. The second resonance (high frequency) is due to the high density region of plasma in the central part of the radial density profile; this resonance happens in consequence at a higher frequency value, respect to the first one. When the distance between the probes is small ($D \leqq 10cm$), the partial characteristics, to which the second resonance belongs, is practically due only to the high density plasma located directly between the ion sheaths surrounding the probes. When the probes are moved away, regions of plasma, of lower density, along the axial and radial directions contribute more and more to this second partial characteristics. As a consequence, the frequency of the antiresonance of the second partial characteristics, which represents an average plasma frequency of the plasma between the probes, decreases, and the frequency of the corresponding partial resonance decreases too, as seen in Fig 5.1.

The second resonance (high frequency) is prevalent on the first (low frequency), for small distances between the electrodes; the decay of the second resonance versus D is faster anyaway than the decay of the first, moreover, for large distances between the electrodes, (D > 30cm) the second resonance is weaker than the first (Fig 5.2). These facts happen because the growth of the impedance met by the lines of force of the r.f. field, directly connecting the probes along the radial direction (internal loop), is larger, for growing values of D, than the growth of the impedance of the external loop, connecting the probes through the low density tail of the plasma, away axially. For small distances D, the impedence of the internal direct loop is smaller than the impedence of the external, due to the small distance and to the large density between the probes. For large distances D, the opposite happens, cause of the larger section of the external loop. The amplitude of the two resonances, are proportional to the admittances of the two loops. For intermediate distances (D ~ 20cm) the impedences of the two loops have the same importance, and the amplitudes of the two resonance peaks are equal. The features of the total characteristic , considered as a superposition of the two partial characteristics described above, fit qualitatively the results shown in Figs 5.1 and 5.2.

The frequency of the high frequency antiresonance of the combined r.f. characteristic, depending on both the contributing characteristics does not represent exactly the plasma frequency corresponding to the average density between the radial probes. Only for short distances (D < 10~15cm) the measured plasma frequency can be considered as an average value corresponding to the density in the region between the probes; this average has to be considered as done also on the axial decay. The value of 10 Mc/s measured for D=10cm is in good agreement with the value of 8.97 Mc/s calculated from the density of 10^6 el/cc on top of the radial profile. For distances D larger than 15cm, the antiresonance, due to the low density part of the plasma, affects the antiresonance of the total r.f. characteristic; in consequence the frequency of the antiresonance of the r.f. characteristic does no more represent the average plasma frequency in the region between the probes.

The low density case (low acceleration voltage), where only one resonance is found, can be interpreted by considering how the radial density profiles are modified for decreasing acceleration voltages of the plasma source. By considering Fig 3, which shows how the elbow connecting the wings of the radial density profile shifts to lower radiuses, for lower acceleration voltages, it can be concluded that the main difference, between the high density and the low density cases, consists in the fact that, in the low density situation, the high density part of the density profile is confined to a narrower region around the axis of the plasma vessel, and is less prevalent on the low density part. The frequency of the antiresonance (Fig 6.1) does not vary, for distances of the probes between 10cm, 20cm, and, for larger distances, its decay is weaker than the decay of the total high frequency antiresonance in the high density case; this fact is in agreement with a less critical dependence of the whole characteristic on the internal core of the radial density distribution. The high frequency and the low frequency resonances in this case have the same importance and their frequency separation is small; as a consequence the resultant r.f. characteristics presents only one peak. The frequency of the antiresonance represents in this case, also for large distances D, the average plasma frequency of the plasma between the probes. In terms of equivalent electric circuit, the high density case can be represented by the circuit shown in Fig 8.3, where ε_1 and C_1 represent the dielectric constant and the capacity of the high density plasma, while ε_2 and C_2 are the same quantities for the low density plasma. Cs_1 is the capacity of the ion sheath around the probes of the high density loop, while Cs_2 is the same quantity, for the low density loop. The admittance of such a circuit presents two resonances and two antiresonances. The low density case, where the high density and the low density loops are not separated, is represented by the circuit shown in Fig 8.4, whose admittance has only one resonance and one antiresonance.

More evidence, about the interpretation given above, can be gained by performing the radial transmission measurements placing the radial probes in the central plane of the metal vessel, 26cm away axially from the previous position. The radial density distribution, measured in such a plane for a high density type plasma, is almost flat, and the axial density profile, in the region between the probes, consists of the exponential low density tail. This situation is qualitatively similar to the low density case, described before; the resonance characteristics, measured for different distances between the probes, in a high density type plasma, presents only one resonance. Fig.9 shows the behavior of the peak and of the antiresonance, whose frequency dependence on the distance between the probes, is quite weaker than in the low density case.

§ 5. Axial Transmission

Transmission measurements were performed by using the longitudinal movable electrode as a detecting probe; the r.f. power was transmitted always by the radial probe used before, kept at a distance of 12.5cm from the axis. The r.f. characteristics was measured axially for different positions of the longitudinal probe, in a high density type plasma, which in the radial direction showed double resonance.

Fig.10.1 shows the axial density decay during the r.f. measurements. The characteristic shows similarity to the one found in the transversal measurements, because a combination of high frequency and low frequency resonances is found. The difference consists in the fact that, for positions of the axial probe, less than 10cm from the plane where the radial electrodes are located (reference position 0) the high frequency resonance is very much prevalent on the low frequency one, which is reduced just to a shoulder, while, for large distances ($L > 20$cm) the opposite thing happens. For the axial distance of 12.5cm, only one broad peak is found.

Fig.10.2 shows the behavior of the resonances versus the distance L of the axial probe from the reference plane where the radial probes are located. The physical situation is practically similar to the high density case for the radial measurements; the lines of force of the r.f. field divide in two ways, one across the high density part of the plasma, in the central bulk, and the other across the low density part, in the external wing of the radial distribution. In this geometrical situation the paths followed by the lines of force in the high density region and in the low density one, are no more well separated as in the radial transmission case; for this reason the double peak structure is less evident, and for very small and very large distances the secondary resonance peak becomes just a shoulder. For small axial distances from the initial position L < 15cm, the antiresonance represents the average plasma frequency between the transmitting and the receiving probes, due to the prevalence of the high frequency peak. For larger distance it is hard to associate to the antiresonance a meaning of average value, for the plasma frequency between the probes.

In conclusion, the radial and axial r.f. measurements indicate that the presence of a double resonance in the r.f. transmission characteristic, across a non homogeneous plasma, is due to the possibility, bound to the geometary of the transmission system, for the r.f. electric field, of resonating with two separate regions within the plasma, having different densities.

Useful discussions with Prof. T. Ichmiya, Dr. T. Dote, Dr. H. Ichikawa and Prof. H. Ikegami are acknowledged with pleasure. The authors thank Dr. T. Kawabe for his interest in this experiment and for stimulating discussions. G. Lampis thanks the Japanese Society for the Promotion of Science for sponsoring his fellowship in the Institute of Plasma Physics of Nagoya University.

References

1) J. A. Waletzko; Research Laboratory of Electronics MIT Quarterly Progress Report No. 80. P.103.

2) H. Ikezi and K. Takayama; Journal of the Physical Society of Japan, vol. 21, (1966) 2021.

3) J. Uramoto, J. Fujita, H. Ikegami and K. Takayama; IPPJ. No. 19

4) G. Peter; Rep. IPP. 254.
Institute für Plasma Physik Garching bei München, Germany.

5) K. Takayama, H. Ikegami, and S. Aihara; Proceedings of the Eighth International Conference on Phenomena in Ionized Gases, Vienna (1967) Paper 6,3,3.

6) S. Takamura, Y. Tanaka; IPP. Annual Review (1966-1967) P.70.

FIG. 1.

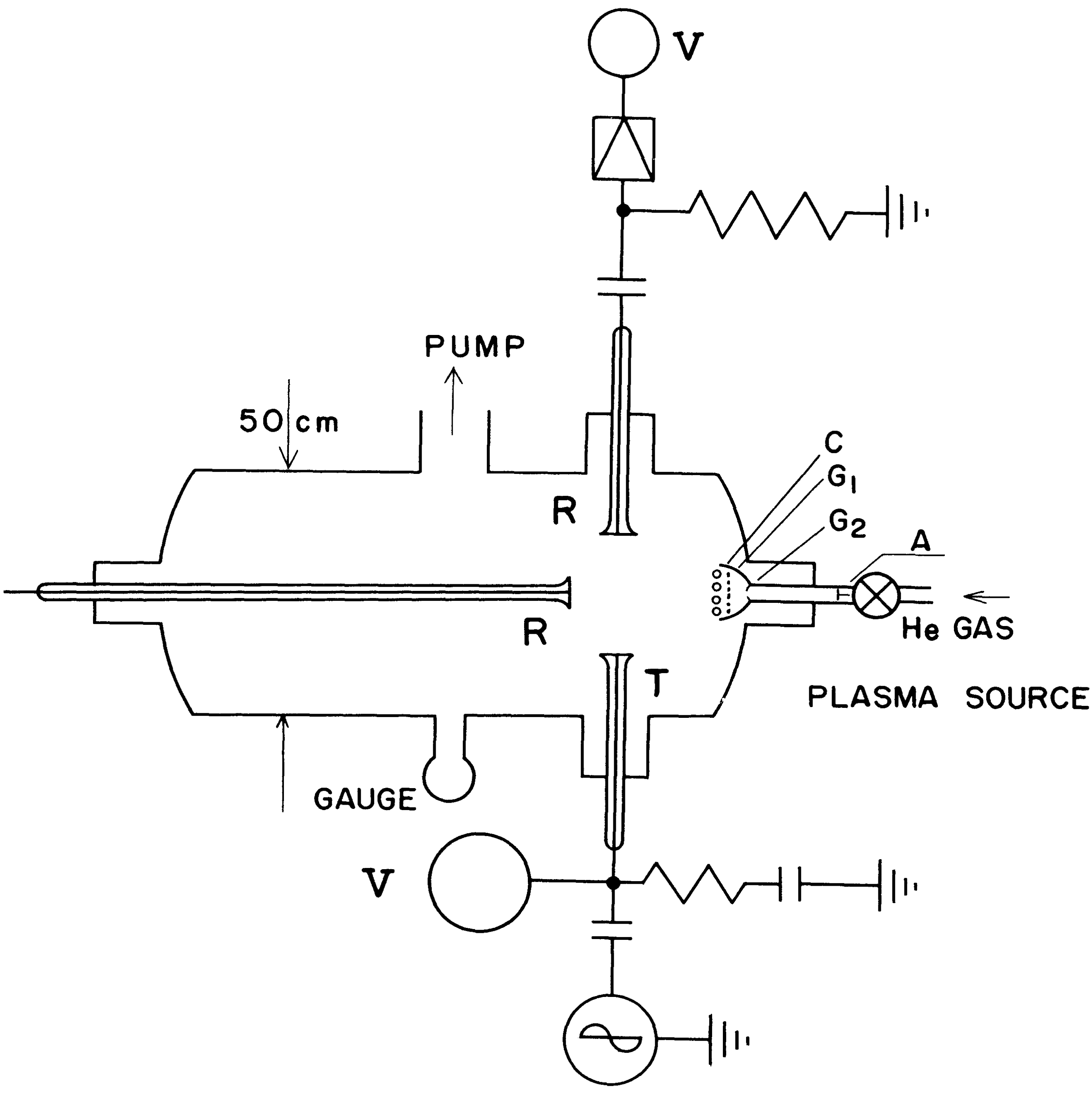

Fig. 1. Experimental apparatus

C: Cathode; G_1: Grid 1; G_2: Gride 2; A: Anode

V: Vacuum tube voltmeters

T: Transmitting probe

R: Receiving probes

FIG. 2.

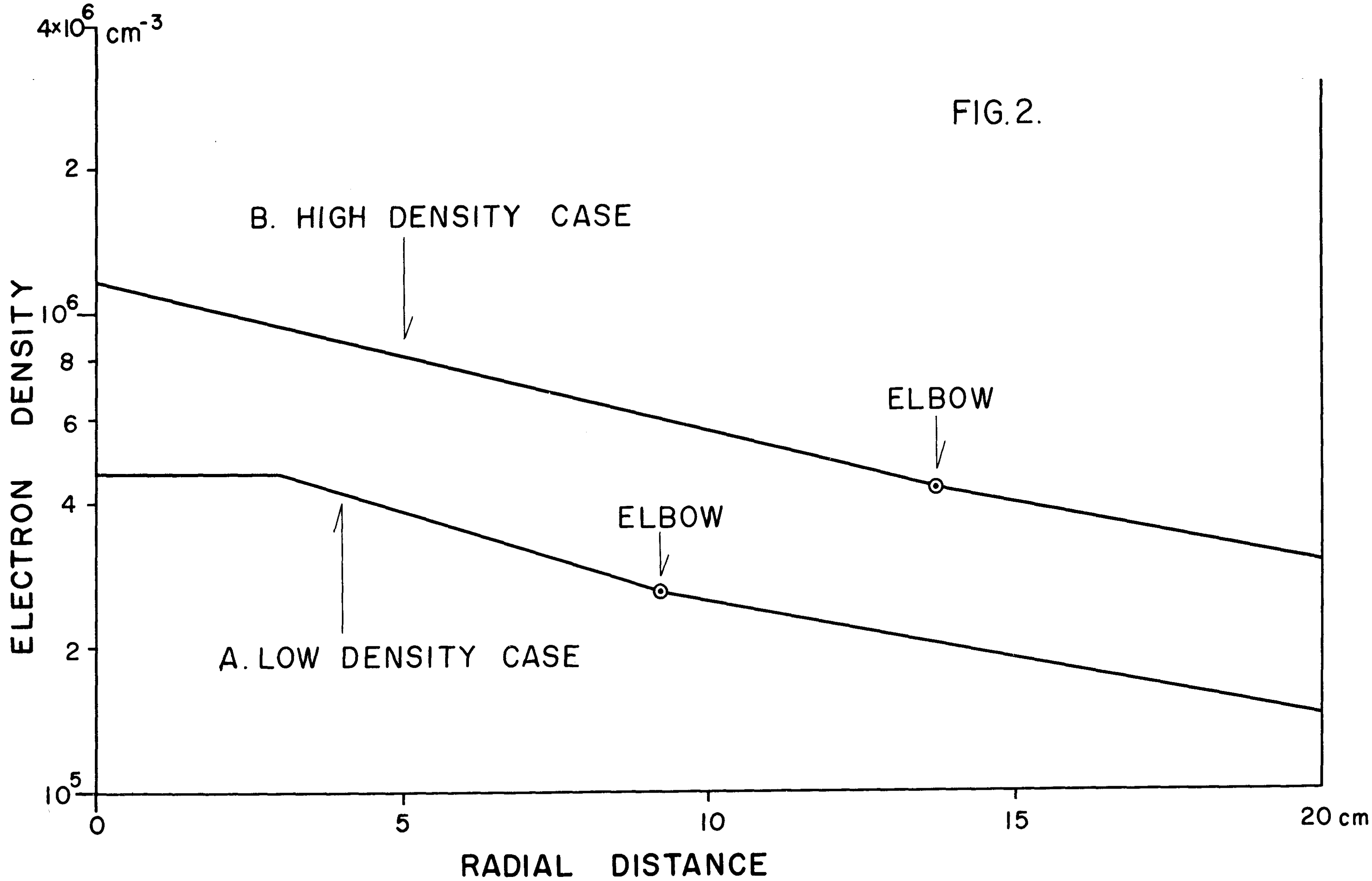

Fig. 2. Radial density profiles

FIG. 3.

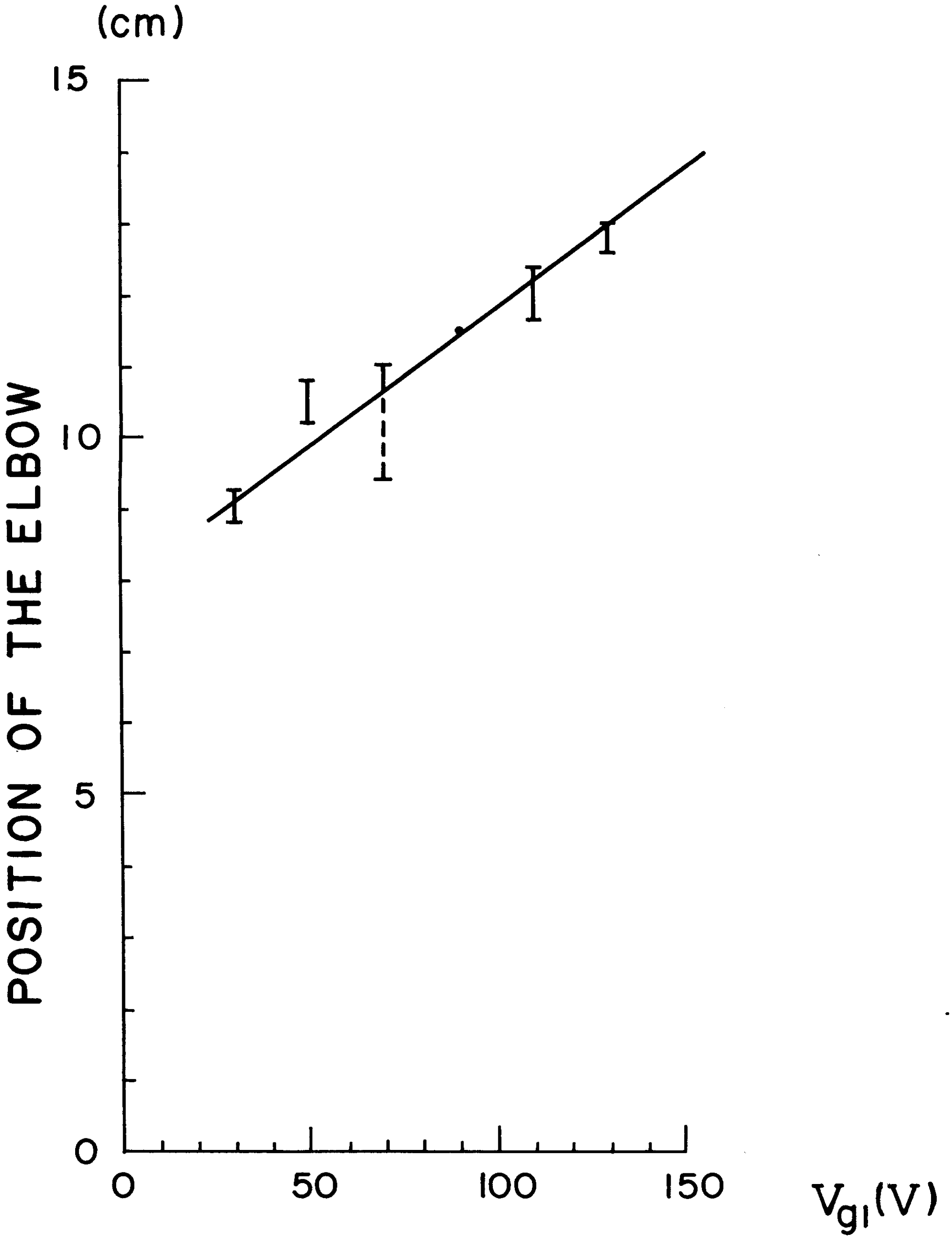

Fig. 3. Position of the elbow, between the internal and the external wings of the radial density profile, versus acceleration voltage.

FIG. 4.

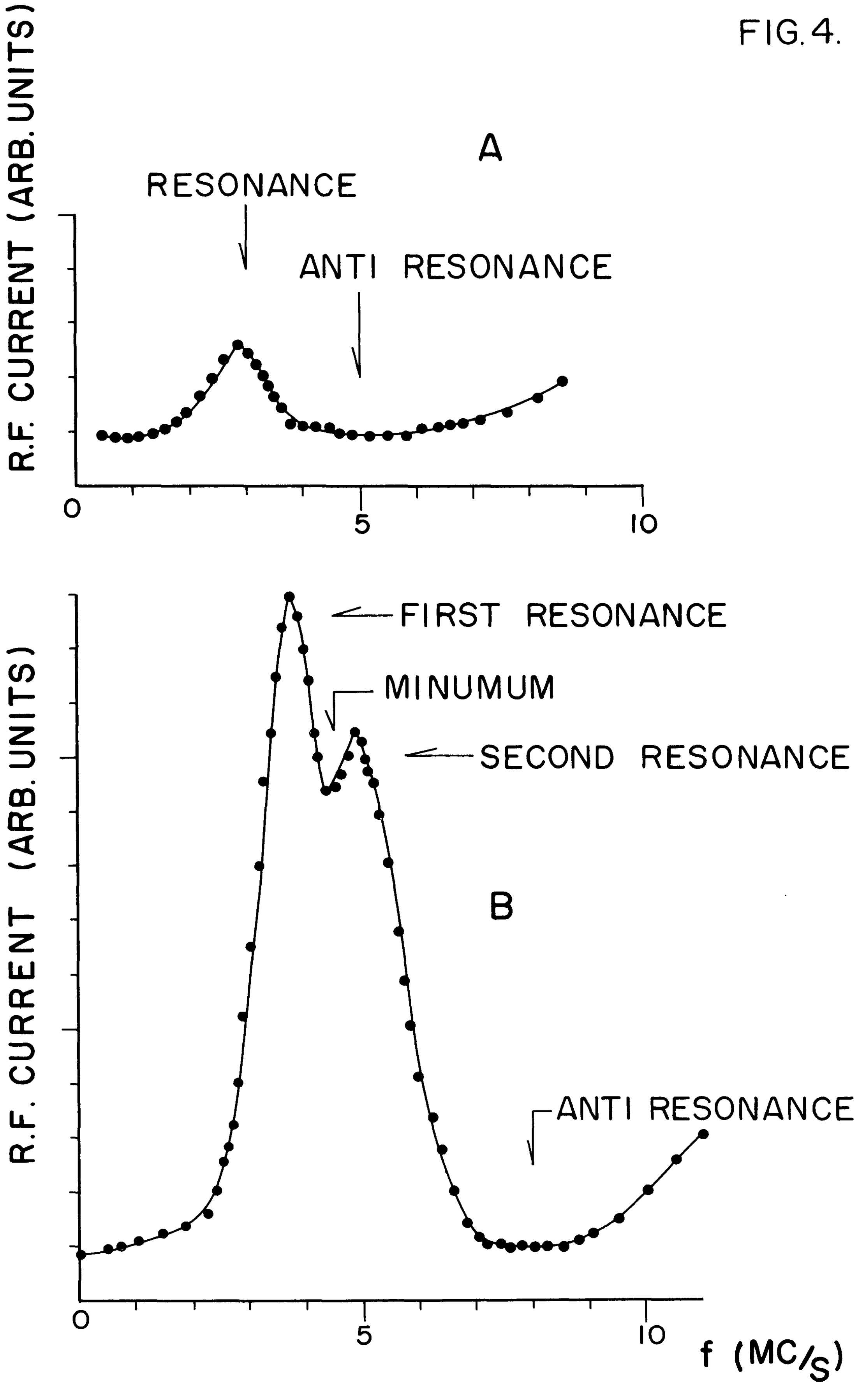

Fig. 4. Radiofrequency characteristics
(Distance D between the radial probes = 25cm)

A. Low density type

B. High density type

FIG.5.1.

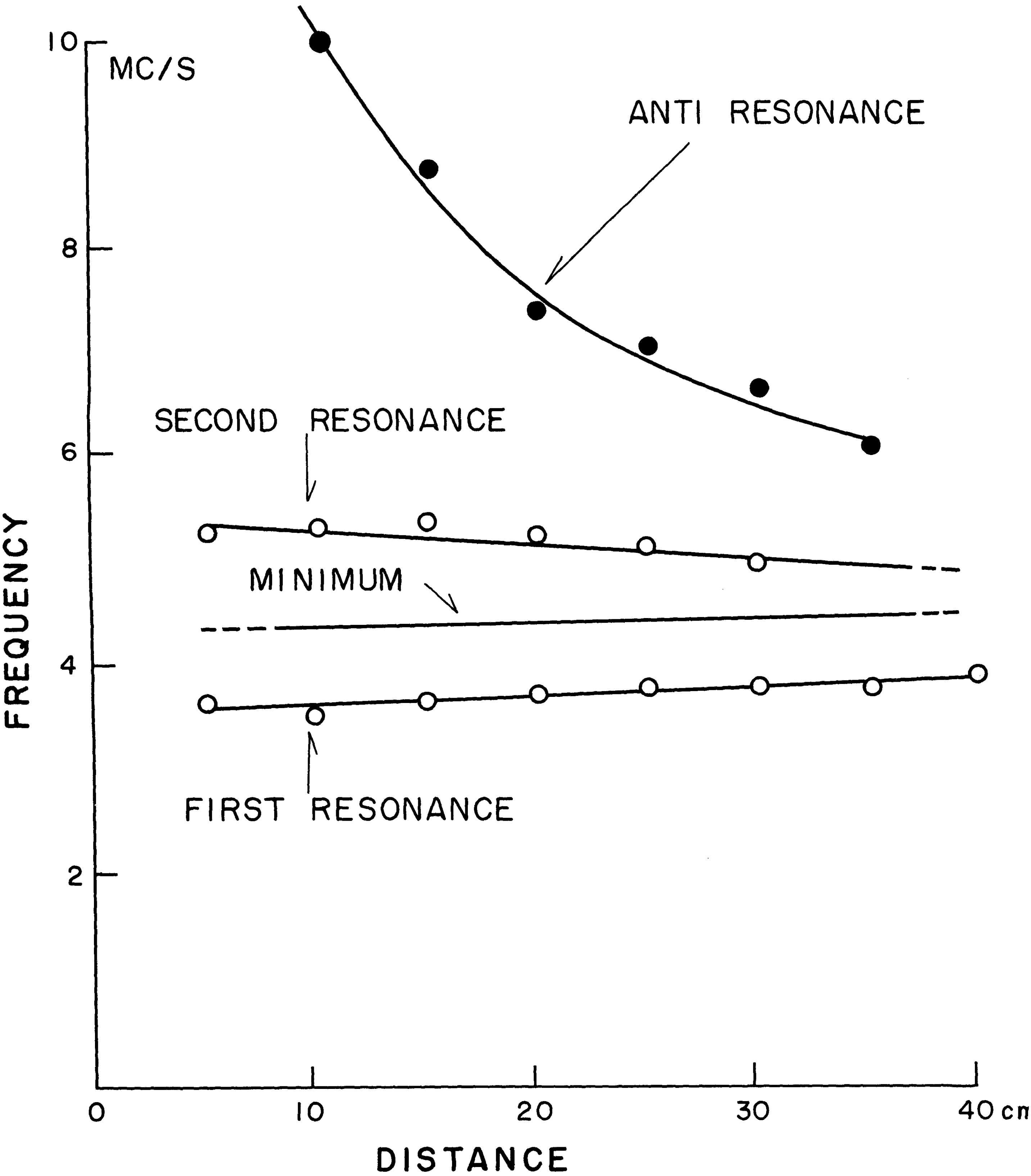

Fig. 5.1. Dependence of the frequency of the resonances and of the minima on the distance between the radial probes. High density case.

FIG. 5.2.

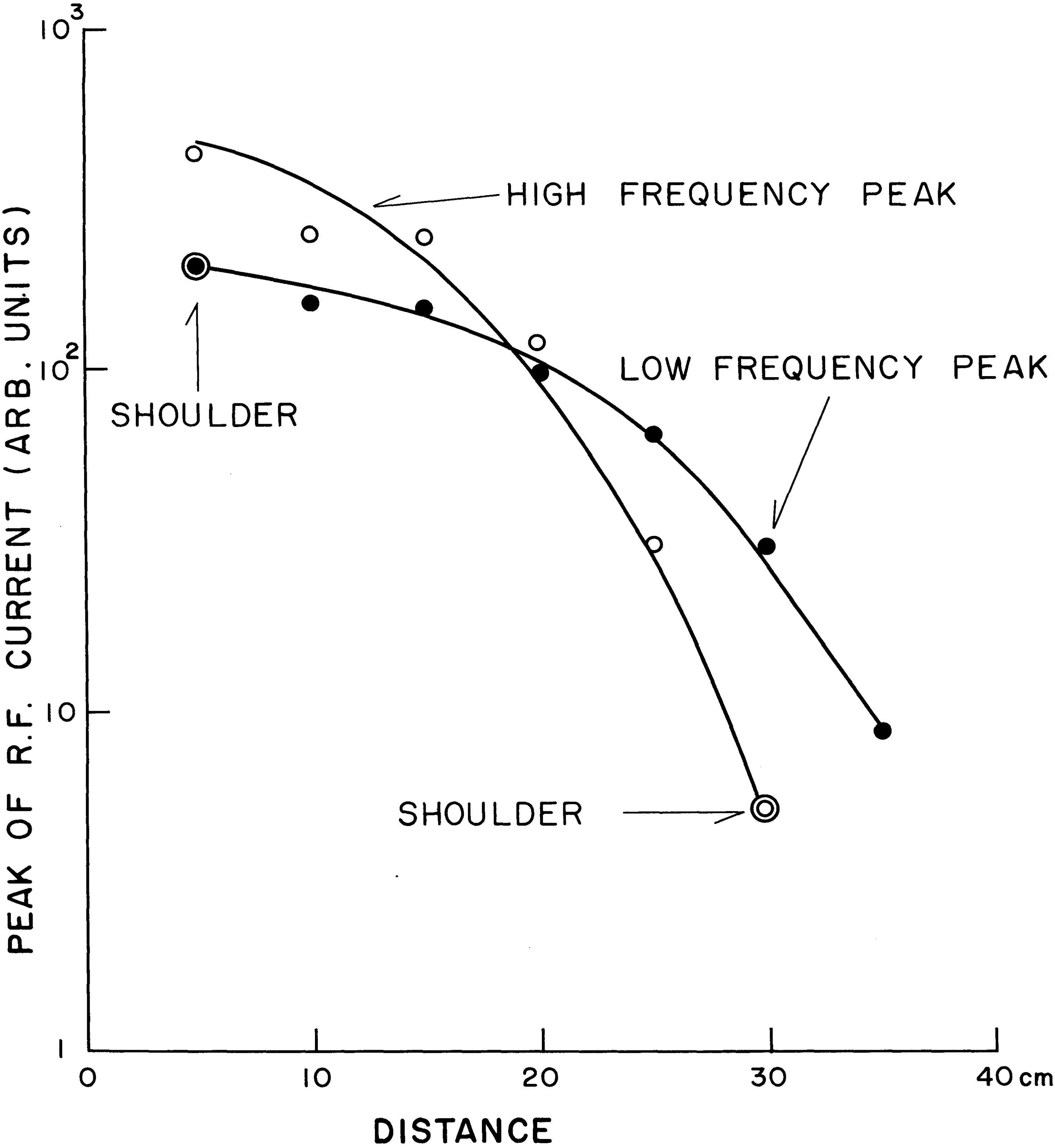

Fig. 5.2. Dependence of the amplitude of the resonances on the distance between the radial probes. High density case.

FIG.6.1.

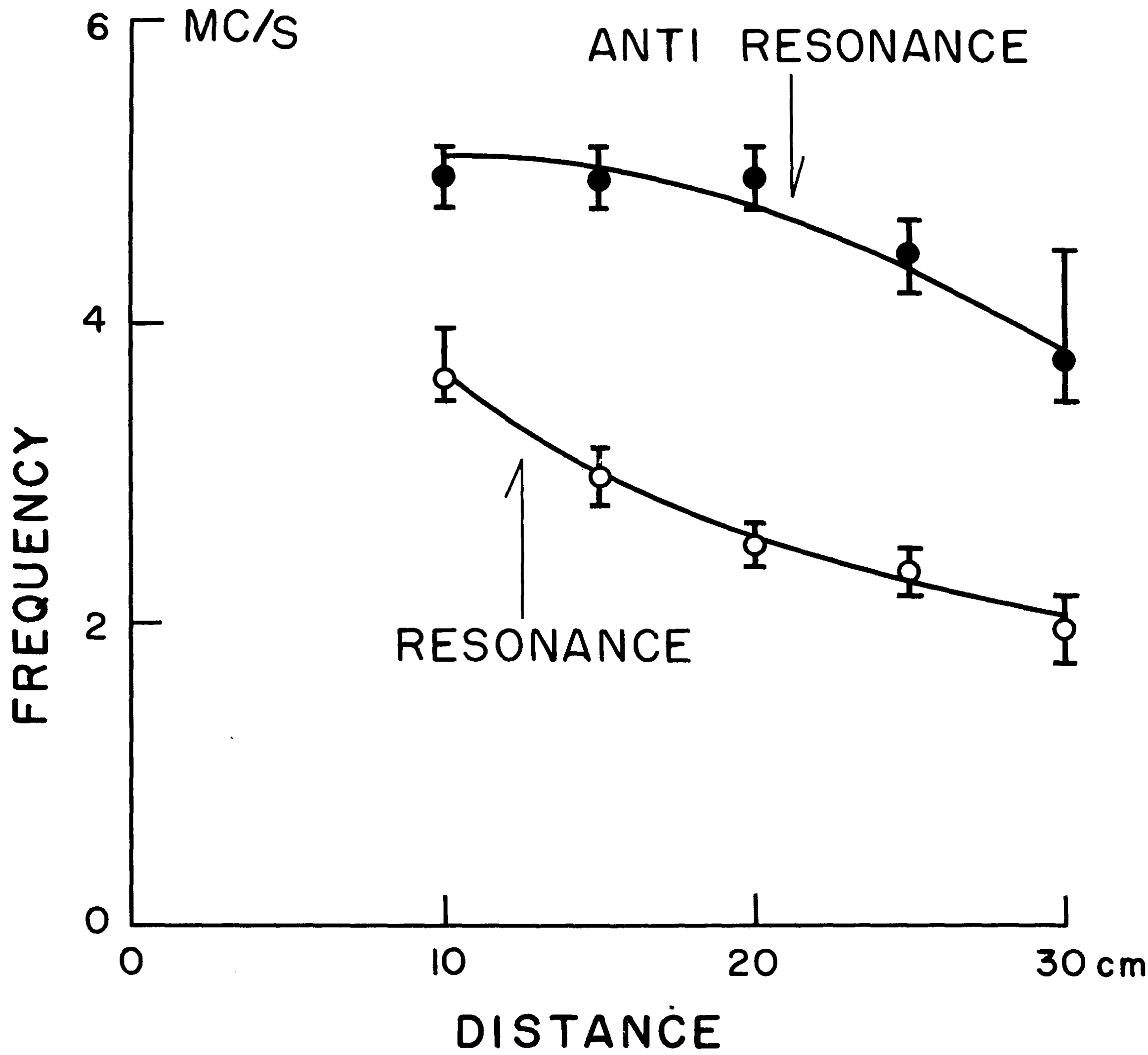

Fig. 6.1. Dependence of the frequency of the resonance and of the antiresonance on the distance between the transmitting and the receiving probes.
Low density case.

FIG.6.2.

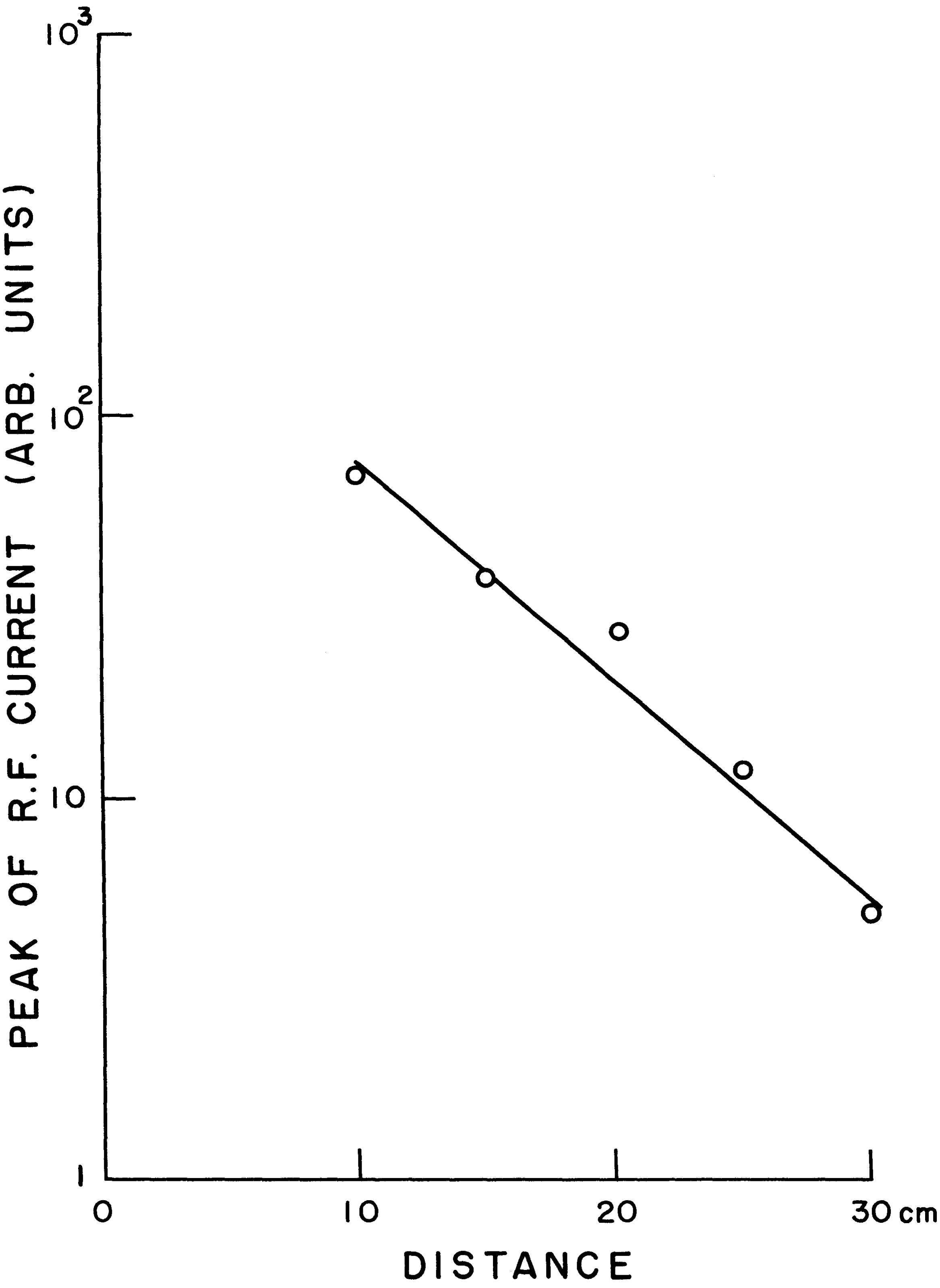

Fig. 6.2. Dependence of the amplitude of the resonance on the distance between the transmitting and the receiving probes. Low density case.

FIG. 7.1.

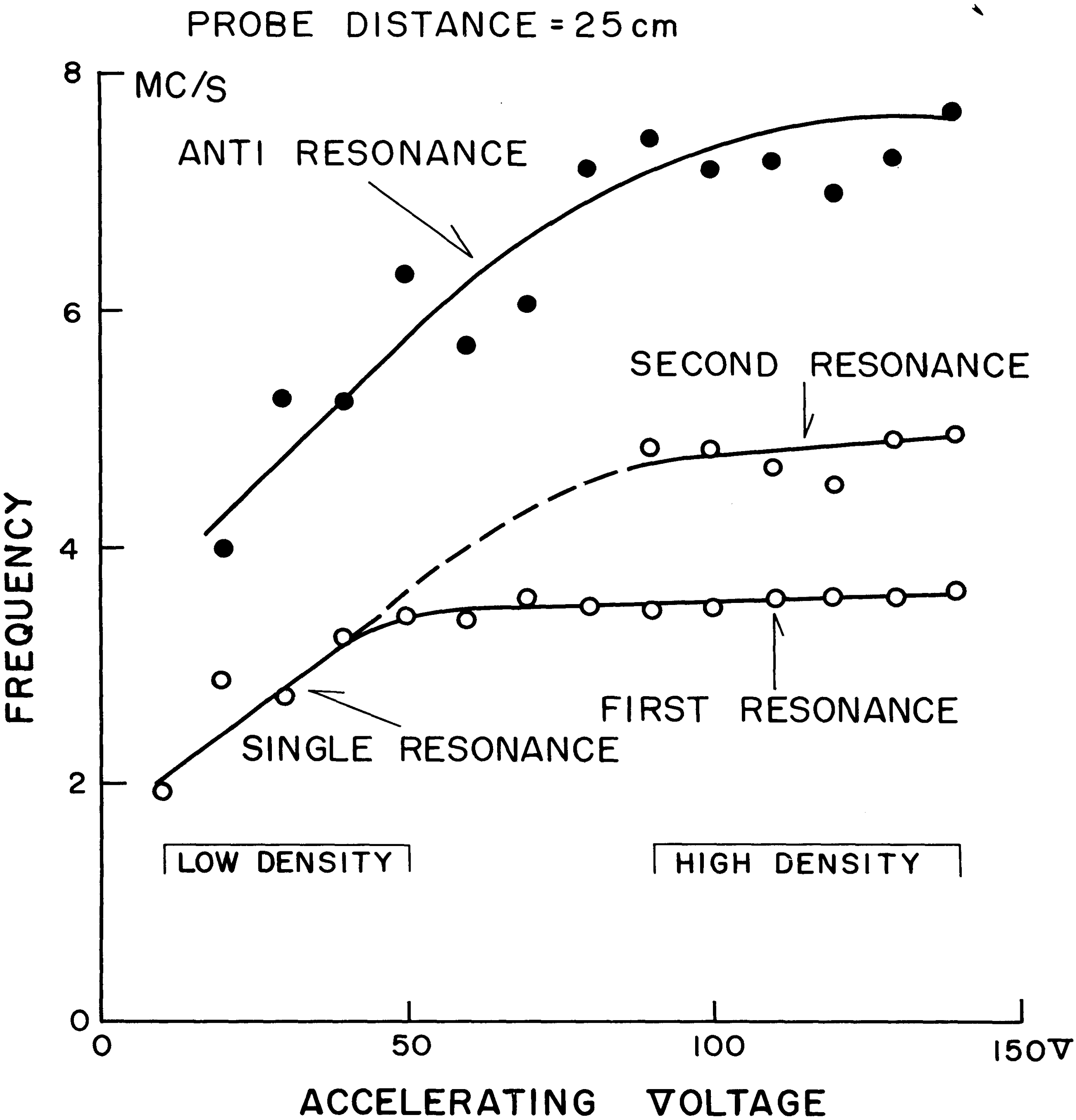

Fig. 7.1. Transition from the low density to the high density case, for growing acceleration voltages.
Frequency variation of the resonance, from single to double.

FIG.7.2.

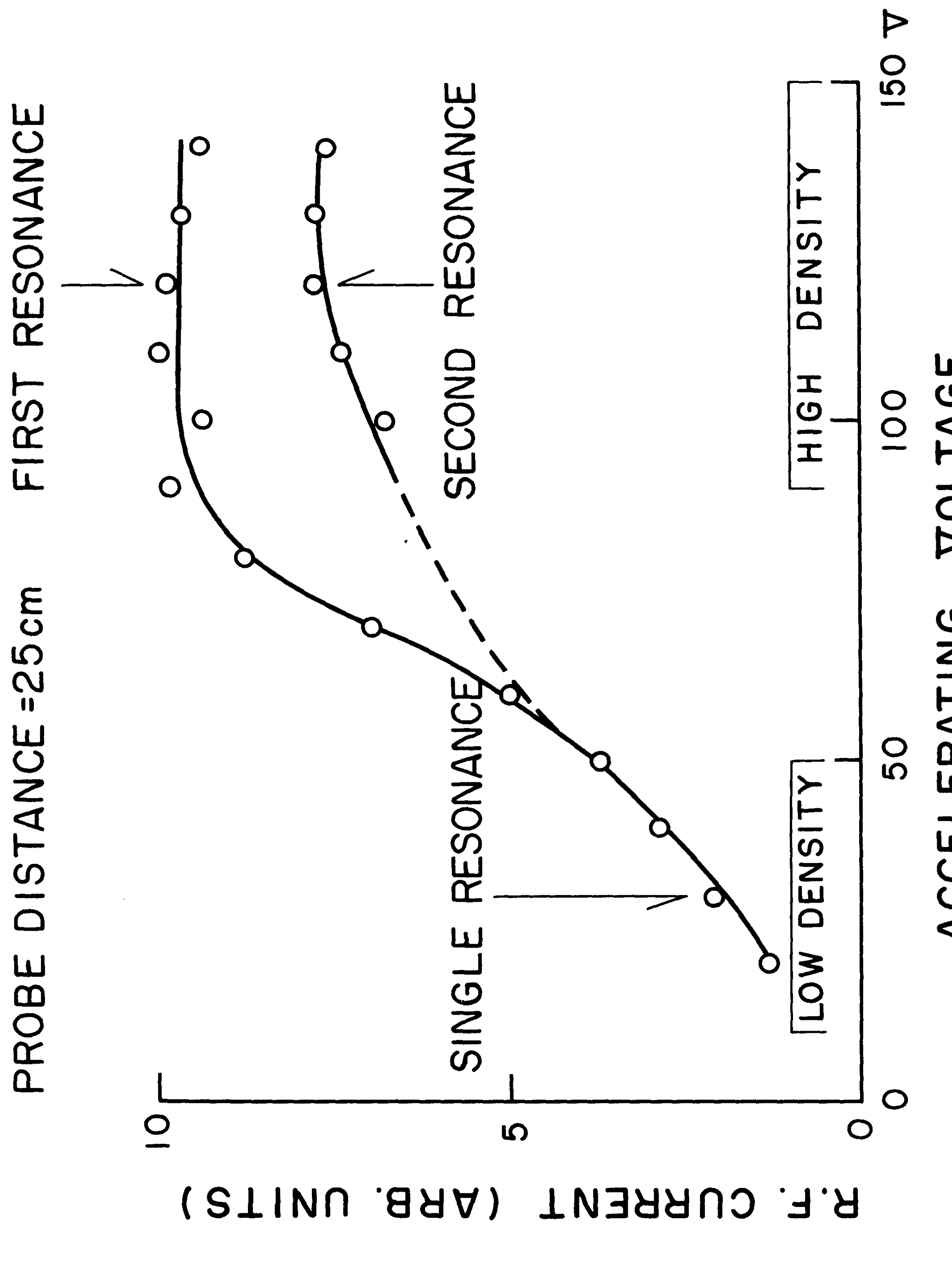

Fig. 7.2. Transition from the low density to the high density case, for growing acceleration voltages.
Amplitude variation of the resonance, from single to double. The distance between the radial electrodes is 25cm.

FIG.8.1.

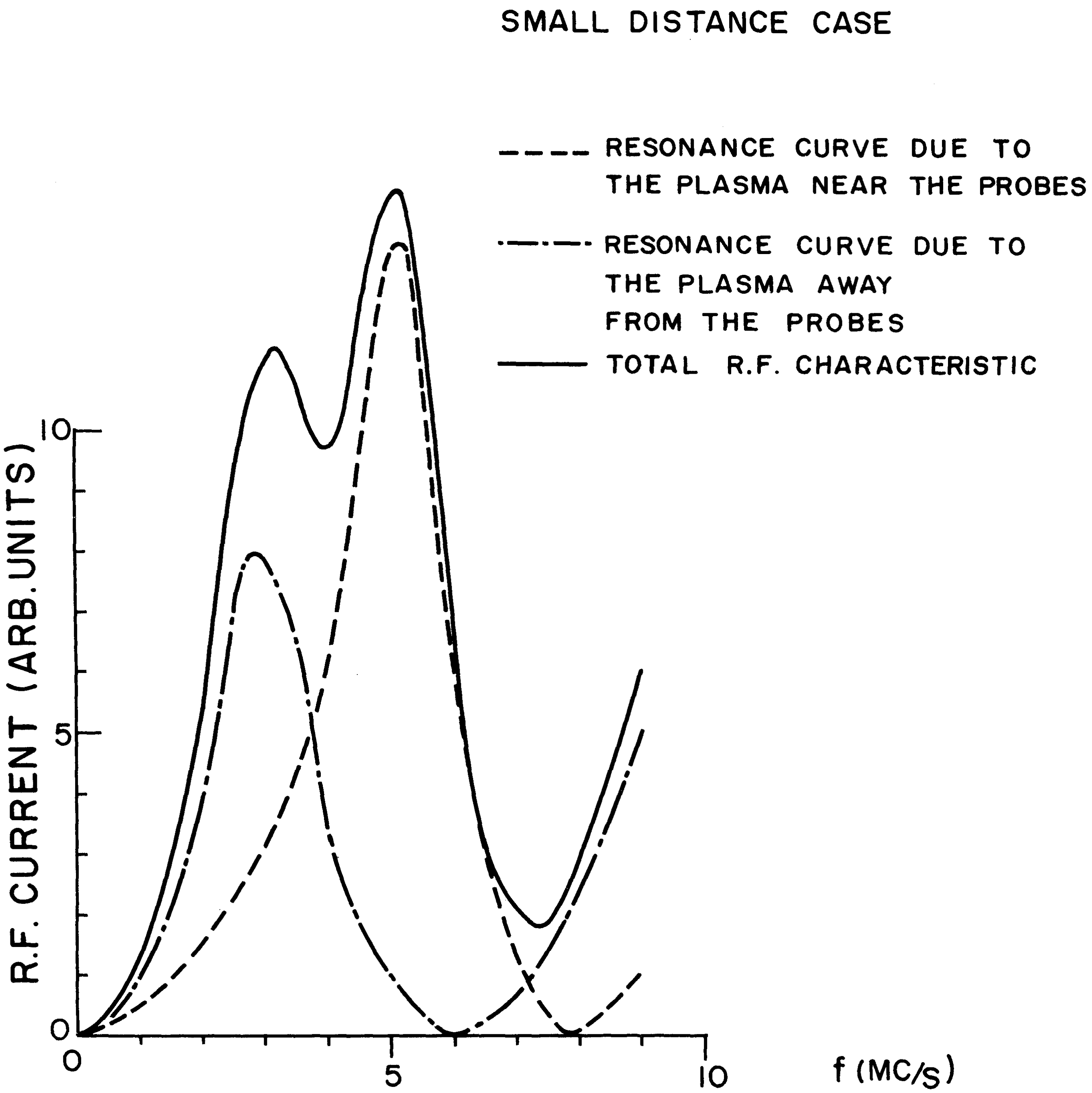

Fig. 8.1. Model explaining the high frequency and the low frequency resonances. Small distances (D = 10cm). Structure of the characteristics.

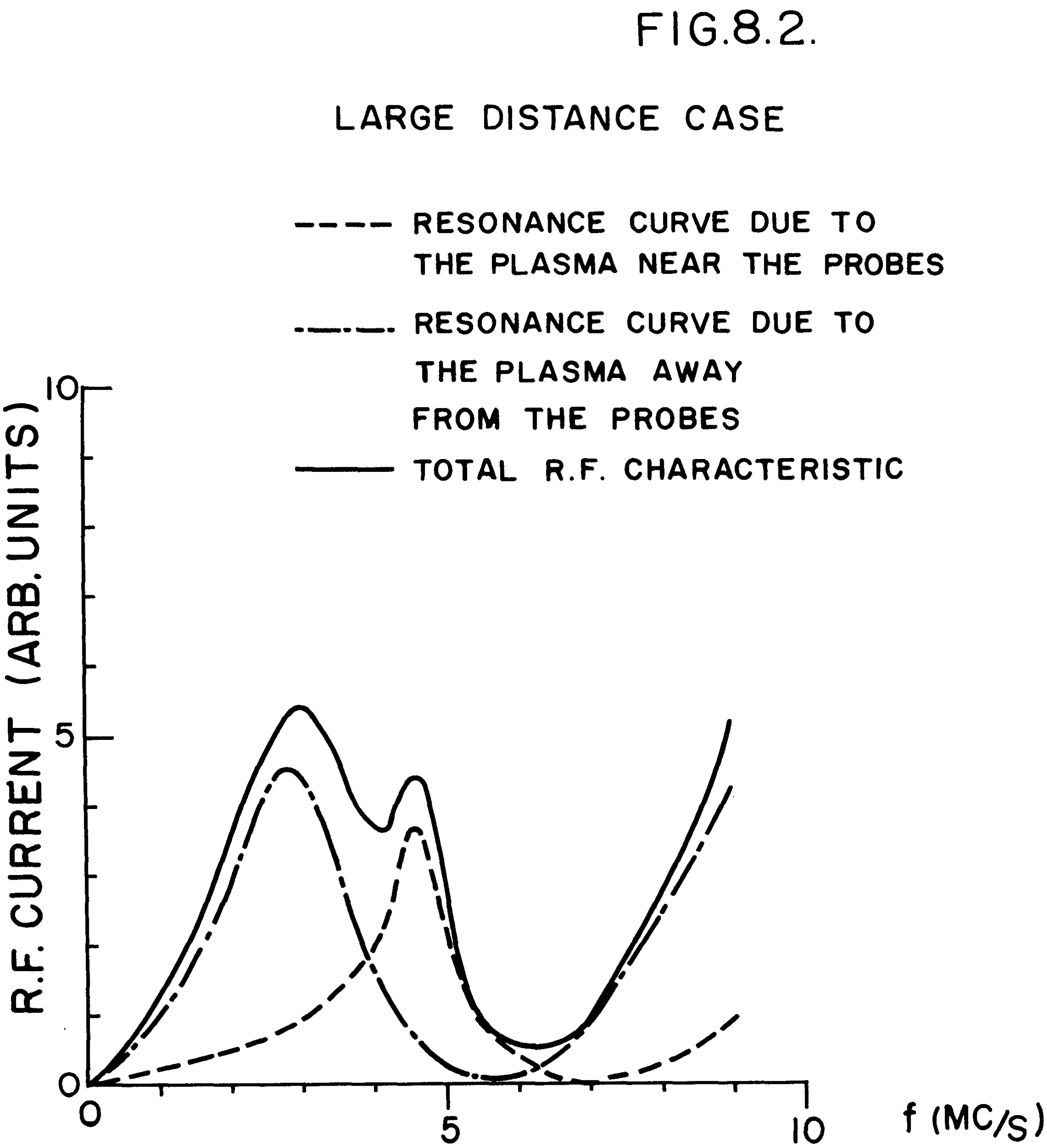

Fig. 8.2. Model explaining the high frequency and the low frequency resonances. Large distances (D = 30cm). Structure of the characteristics.

FIG 8,3

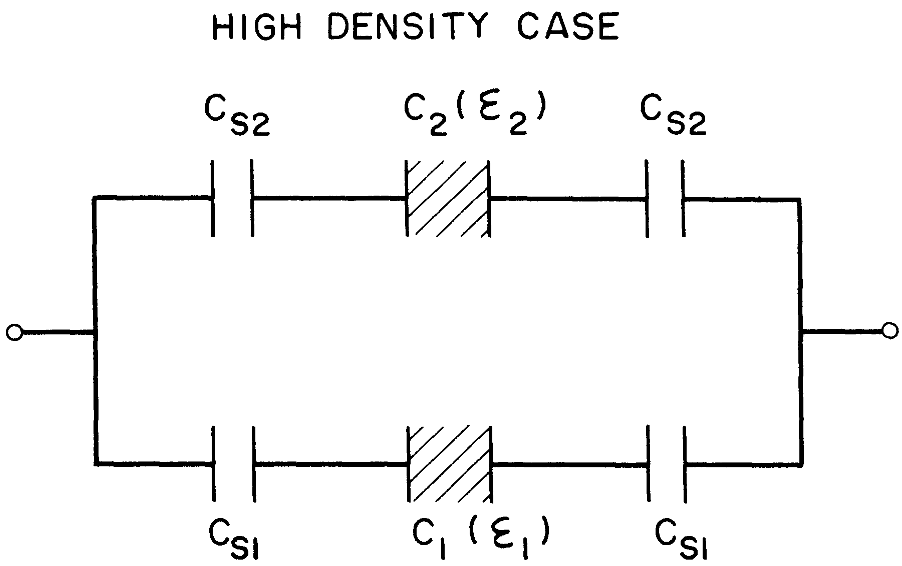

Fig. 8.3. Model explaining the high frequency and the low frequency resonances. Equivalent circuit: high density case.

FIG 8,4

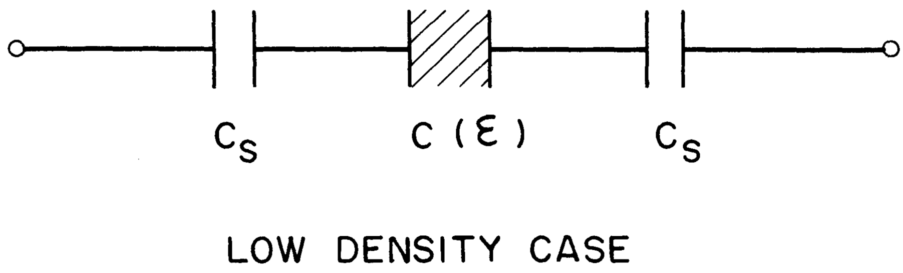

Fig. 8.4. Model explaining the high frequency and the low frequency resonances.
Equivalent circuit: low density case.

FIG. 9.

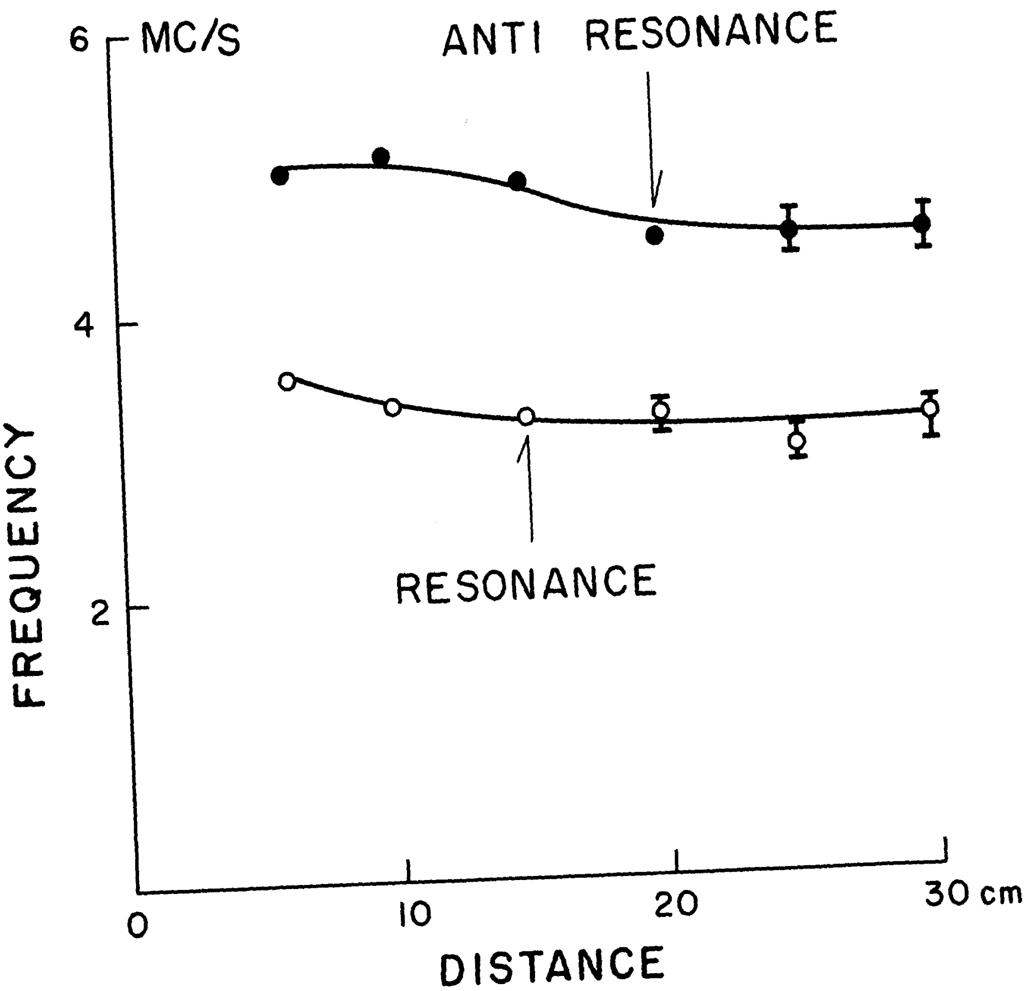

Fig. 9. Dependence of the frequency of the resonance and of the antiresonance, on the distance D between the probes, for a high density type plasma. The probes are located in the central plane of the metal vessel.

FIG.10.1.

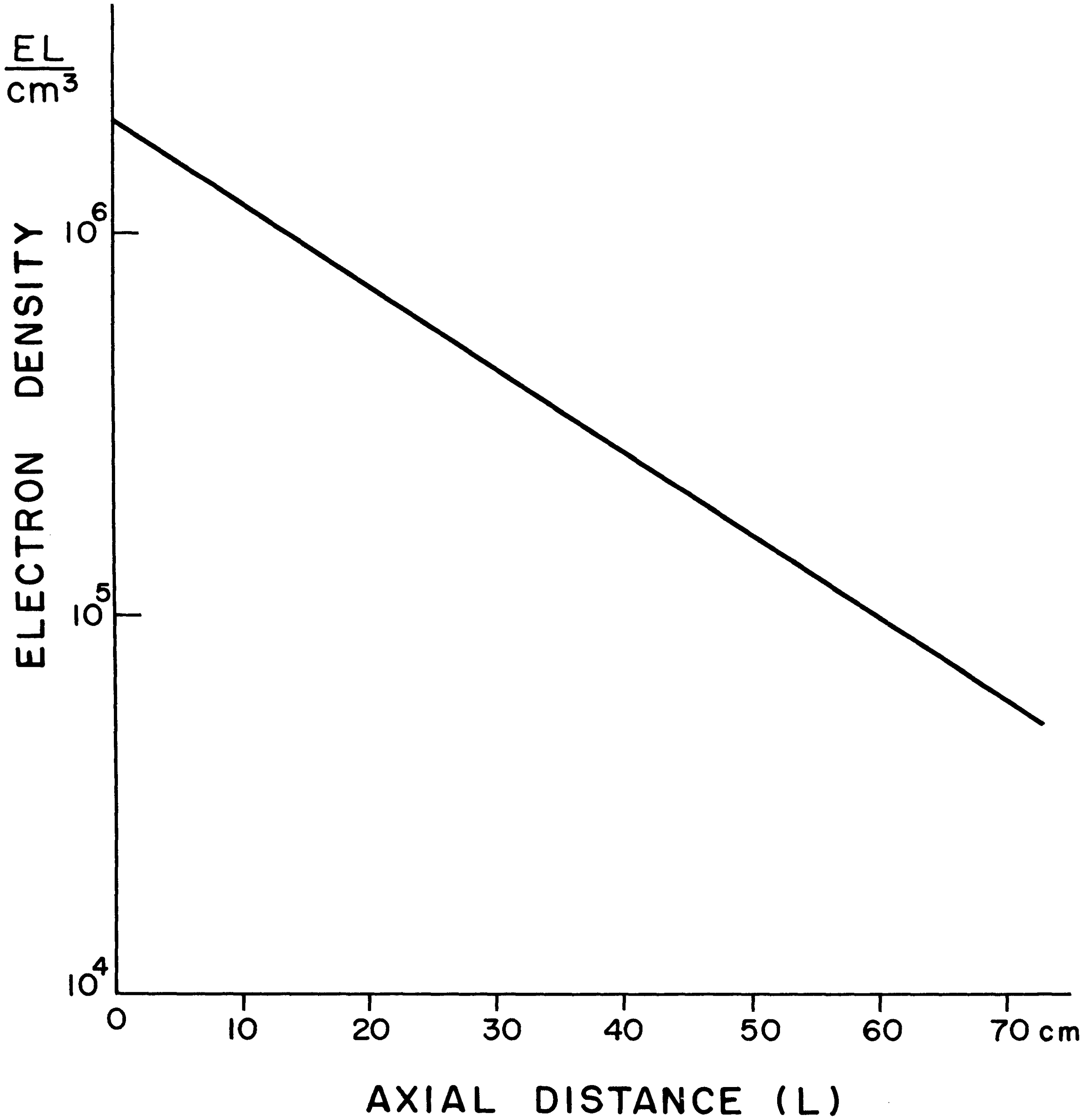

Fig. 10.1. Axial density decay, during the longitudinal r.f. measurements. High density case. The distance L is measured from the plane where the radial probes are located.

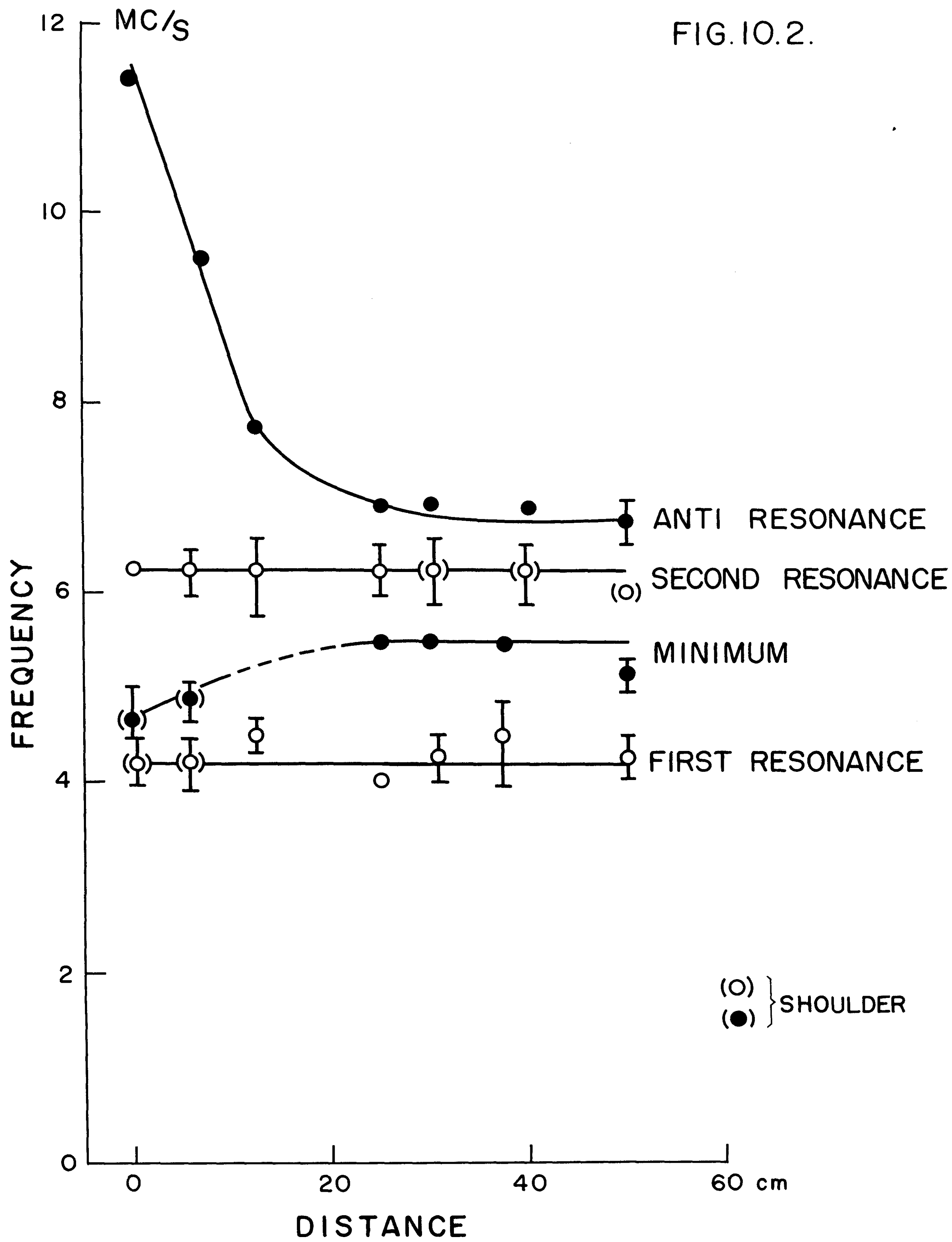

Fig. 10.2. Variation of the frequency of the resonance peaks and of the minima for different axial positions of the receiving probe.