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LOWER HYBRID EMISSION DIAGNOSTICS ON THE NASA LEWIS BUMPY TORUS

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ABSTRACT

The feasibility of using R. F. emission near the lower hybrid frequency of the NASA Lewis Bumpy Torus plasma for diagnostic purposes is examined. The emission is detected using a spectrum analyzer and a 50 Ω miniature coaxial antenna that is sensitive to the polarization of the incoming signal. The frequency shift of the lower hybrid emission peak is monitored as a function of the background pressure, electrode voltage, electrode ring configuration and the strength of the toroidal dc magnetic field. Simultaneous measurements of the average plasma density are made with a polarization diplexing microwave interferometer. The experimental results presented here extend our previous work to include negative electrode voltages and plasma densities up to $10^{12}/cm^3$. The information derived from the experiment is discussed with reference to the following: (a) the strength of the d. c. magnetic field in the emitting region, (b) comparison of the lower hybrid plasma density with the average plasma density and (c) validity of the cold plasma lower hybrid resonance formula in the high density operating regime of the bumpy torus plasma.

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INTRODUCTION

Fluctuations near the lower hybrid frequency of the NASA Lewis Bumpy Torus plasma were first identified in the low pressure mode of operation using 12 negative electrode rings and average electron densities in the range 10^9 - $10^{11}/cm^3$ (ref. 1). Later, lower hybrid emission was also detected with 12 positive electrode rings in the high and low pressures regions of operation with electron densities being in the range 10^9 - $3\times10^{10}/cm^3$ (ref. 2). Recently, however, the bumpy torus has been operating with less than 12 electrode rings and primarily with negative polarities on the electrode rings. In such a mode of operation particle confinement times have improved considerably and average electron densities in excess of $10^{12}/cm^3$ have been achieved (ref. 3). Lower hybrid emission experiments under these improved operating conditions of the plasma are given special emphasis and some additional data on positive polarity operation of the plasma is also described. The feasibility of using L. H. emission data for diagnostic purposes and the behavior of this emission peak as a function of the plasma parameters is discussed.

EXPERIMENTAL APPARATUS

The R. F. detection system used in the lower hybrid emission experiments was described in reference 2. It consists of a 50 Ω miniature coaxial line, with 1 cm of the center conductor exposed. The coaxial line is concentrically located in a re-entrant quartz tube that is inserted into the vacuum tank through an airlock. The coaxial antenna leads to a spectrum analyzer capable of scanning emission in the range 1 MHz to 1. 3 GHz. In addition to the 50 Ω coaxial radial probe antenna that was previously used, a circular loop antenna has been developed. This probe has been found to be sensitive to the polarization of the incoming electromagnetic signal, that is, by orienting the plane of the loop at different angles with respect to the toroidal axis of the plasma, the amplitude of the emission peak has been observed to change significantly. A comparison of the radial probe and circular probe with two loop orientations differing by 90^{o} is shown in figure 1 for identical operating plasma conditions. It may be observed from this figure that the amplitude of the 56 MHz peak is different in each of the photographs. The radial probe barely picks up this peak, while there is a difference of at least 10 dB on the arbitrary vertical scale between the amplitudes of the 56 MHz peak as received by the circular probe with two different angles of polarization. The frequency response of the circular loop in the range 0-100 MHz is shown in figure 2. Below 20 MHz the response of this probe rolls off quite sharply, but its polarization sensitivity is valuable in detecting emission peaks.

The choice of the port for the location of the tube-probe assembly was also found to be a significant factor in the detection of the emission peaks. Experiments described in reference 2 were conducted by placing the probe almost in line with the anode ring, as shown in figure 3. The results of those positive polarity, low density ($\overline{n}_e = 10^9 - 3\times10^{10}/cm^3$) experiments indicated that the emissions emanated from the magnetic field contours where the $\overline{E}X\overline{B}$ drift action is strongest, that is, where the toroidal plasma passes through the coil dewars. Based on those results and also on the fact that port 8 yielded no prominent data for negative polarity high density operation of the plasma, the probe assembly was placed in port 2, where the antenna is directed toward the region of strong $\overline{E}X\overline{B}$ drift in the plasma and also physically closer to it (see fig. 4).

The aim of the experiment was to look for a moving peak in the frequency range of 0-100 MHz as the plasma parameters were varied. This was not always simple to do as the moving peaks were sometimes enveloped by stationary peaks, the amplitudes of which were dependent on the plasma parameters.

An approximate method has been devised to evaluate the amplitude of the lower hybrid emission peaks. A linear antenna tuned at 30 MHz radiating P = 85 W of power and located at a distance of R = 1 M from the probe antenna was used as a calibrating source. Assuming that the antenna power falls off as $(\lambda/R)^2$, the power as received by the probe antenna is $P(\lambda/R)^2$. The voltage corresponding to the power radiated by the linear antenna was measured on the spectrum analyzer. By also measuring the amplitude of the emission peak (characteristically 0.35 mV RMS) as picked up by the probe, it was determined that if an equivalent linear antenna were to replace the emitting region then the power radiated by such an antenna would be typically 0.20 watts.

EXPERIMENTAL RESULTS

As previously described in reference 2, the experiment consists of monitoring the frequency of a broad amplitude peak as a function of the plasma parameters in the expected frequency range. The experimental results here are presented for the following variations of the plasma parameters, (a) negative electrode polarity, 12 electrode rings, (b) negative electrode polarity, 4, 3, 2 electrode rings, (c) positive electrode polarity, 12 electrode rings. Each of these cases is discussed separately.

(a) negative electrode polarity, N = 12

The experiment for this condition was done for 3 different values of the toroidal dc magnetic field: 2.4 T, 1.92 T and 1.44 T. Figure 5 shows a plot of the experimentally measured emission frequency vs. anode current. As expected the peak frequency increases with the current, which happens to be proportional to the average electron number density.[3] For a given current the frequency is highest for a magnetic field of 1.92 T and not for 2.4 T as might be expected. Figure 6 shows the peak frequency vs. the average electron density $\bar{n}_e$ as measured by the microwave interferometer. The data is shown for the three applied magnetic fields of 2.4 T, 1.92 T and 1.44 T. This data is scattered over an average density variation from 5×10^9 to $8\times10^{10}/cm^3$ and the frequency spread is 20-35 MHz. A comparison of this data with the theoretical variation of the cold plasma lower hybrid resonance as shown in figure 7 and reproduced in figure 6 for B = 2.4 T and 0.4 T, reveals that the experimental data at the higher average electron densities lies outside the possible limits of the dc magnetic field. To have the experimental data lie within the possible limits of the operating magnetic field, it would require that the emission occur at a density lower than the average by a factor of 2.

(b) negative electrode polarity, N = 4, N = 3, N = 2

The data for these configurations of the electrode rings, that is, N = 4, 3, and 2 is similar in many respects. The third and second harmonics of the emission peak were usually observed. The fundamental peak was noticeably of smaller amplitude compared to the second and third harmonics and at times was totally absent. There are two possibilities for this strange behavior: (1) due to a roll-off in the frequency response of the probe below 30 MHz and (2) the density at the plasma boundary may be sufficiently high to reflect the fundamental lower hybrid wave, that is, $\omega_{LH} < \omega_{pi} < 2\omega_{LH}$ at the boundary. As shown in figures 8(a), (b), and (c) for electrode configurations of 4, 3, and 2 rings respectively the peak frequency increases with the current, but appears to saturate at higher currents. Also the peak frequency is higher for lower applied magnetic fields. Figures 9(a), (b), and (c) show the peak frequency as a function of the average density as measured by the interferometer for electrode configurations of 4, 3, and 2 rings respectively. A comparison of these curves with the theoretical cold plasma lower hybrid curves of figure 7 indicates that the discrepancy between the experimental data and the theoretical curves is large. Once again it appears that the emission must be occurring from a region where the electron density is much lower than the average.

The relatively small shift of the peak frequency (figs. 9(a), (b), and (c)) with the average density indicates that large variations in the density of the bulk plasma do not affect the emission peak. Thus, the lower hybrid emission peak in the density range 10^{11} - $10^{12}/cm^3$ must have the region of emission close to the plasma boundary where the densities are much lower than average.

(c) positive electrode polarity, N = 12

Similar data were taken before and described in reference 2. The present data, however, are different in that the probe was placed in port 2, where the antenna is located closer to the suspected region of emission.

Figure 10 shows the peak frequency as a function of the anode voltage for different values of the applied magnetic field. For a given anode voltage the emission peak is higher for a higher applied magnetic field. This observation, however, does not appear to hold for the lower values of the applied magnetic field, that is, B = 1.44 T and 0.96 T. The peak frequency is shown plotted against the average density $\bar{n}_e$ in figure 11. This data spans a density range of 10^9 - 10^{10}/cm^3, which is an order of magnetic lower than the data for N = 4, 3, 2 rings with negative polarity. A comparison of this low density data with the theoretical lower hybrid curves of figure 7 indicates that this data falls well within the limits of the theoretical curves. Thus in this low density range, the lower hybrid emission peak seems to be representative of the bulk plasma, as the plasma parameters are varied.

DISCUSSION AND CONCLUSIONS

The possibility of using the lower hybrid emission as a diagnostic on the NASA Lewis Bumpy Torus has been suggested before (refs. 1 and 2). Some of the important information derived from experiments conducted using this technique are as follows:

(a) The lower hybrid emission peak in the density range 10^9 - 3×10^{10}/cm^3 appears to be dominated by the atomic species of deuterium rather than molecular deuterium. This fact is substantiated by the experimental data described in reference 2 and by the positive polarity (N = 12) data described here. At high densities (10^{11} - 10^{12}/

cm^3) the data lies not only outside the range of the theoretical lower hybrid resonance plot for atomic deuterium (see fig. 7) but also out of the range of a similar plot for molecular deuterium. So a conclusion on the type of species causing emission in the density range 10^{11} - 10^{12}/cm^3 would not be appropriate.

(b) For the experimental data in reference 2 the emitting region was identified as occurring from the bulk plasma between the coil dewars where the $\overline{E}X\overline{B}$ drift action is strongest. The emitting region magnetic field for that data varied from 1.5 to 2.4 tesla for a maximum applied magnetic field of 2.4 T. A figure illustrating this emitting region is reproduced in figure 12 from reference 2. It is believed that the emissions for the high density data reported here occur from the same magnetic contour region but not necessarily from the plasma interior. This argument is substantiated by the fact that the probe antenna had to be physically located close to coil dewars and directed toward the plasma region in between to obtain the experimental data. In the average plasma density range of 10^{11} - 10^{12}/cm^3 the lower hybrid emission density appears to be much lower than the average density. The emitting region corresponding to the high density data, therefore, appears to be close to the boundary plasma layer. The density profile of the toroidal plasma is not known at high densities, and therefore the exact location of the emitting region cannot be specified.

(c) On the basis of experiments described here and in reference 2, the lower hybrid emission may serve as a useful diagnostic in the low density range provided the rf detection system can detect the moving peaks over the background stationary peaks. At high densities, the absence of other supporting diagnostics such as the density profile information cause this technique to be ambiguous.

REFERENCES

1. J. R. Roth and G. A. Gerdin, "Characteristics of the NASA Lewis Bumpy Torus Plasma Generated with High Positive or Negative Applied Potentials," NASA TN D-8211 (1976).

2. R. Mallavarpu and J. R. Roth, "Investigation of Possible Lower Hybrid Emission from the NASA Lewis Bumpy Torus Plasma," NASA TM X-73689 (1977).

3. J. R. Roth, "A Model for Particle Confinement in a Toroidal Plasma Subject to Strong Radial Electric Fields," NASA TM X-73814 (1977).

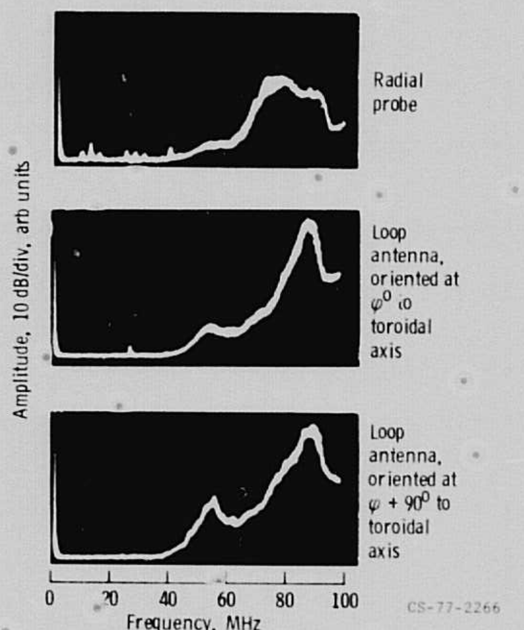

Figure 1. - Comparison of responses of the radial probe and loop antenna for two orientations differing by 90^0.

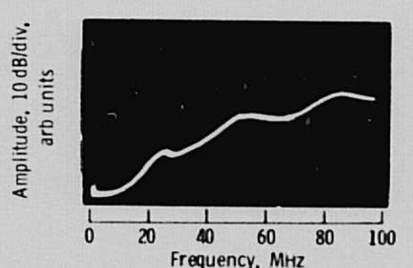

Figure 2. - Frequency response of RF loop antenna.

Contour	Normalized magnetic field strength	Contour	Normalized magnetic field strength
A	0.050	Q	0.850
B	.100	R	.900
C	.150	S	.950
D	.200	T	1.000
E	.250	U	1.050
F	.300	V	1.100
G	.350	W	1.150
H	.400	X	1.200
I	.450	Y	1.250
J	.500	Z	1.300
K	.550	1	1.350
L	.600	2	1.400
M	.650	3	1.450
N	.700	4	1.500
O	.750	5	1.550
P	.800	6	1.600

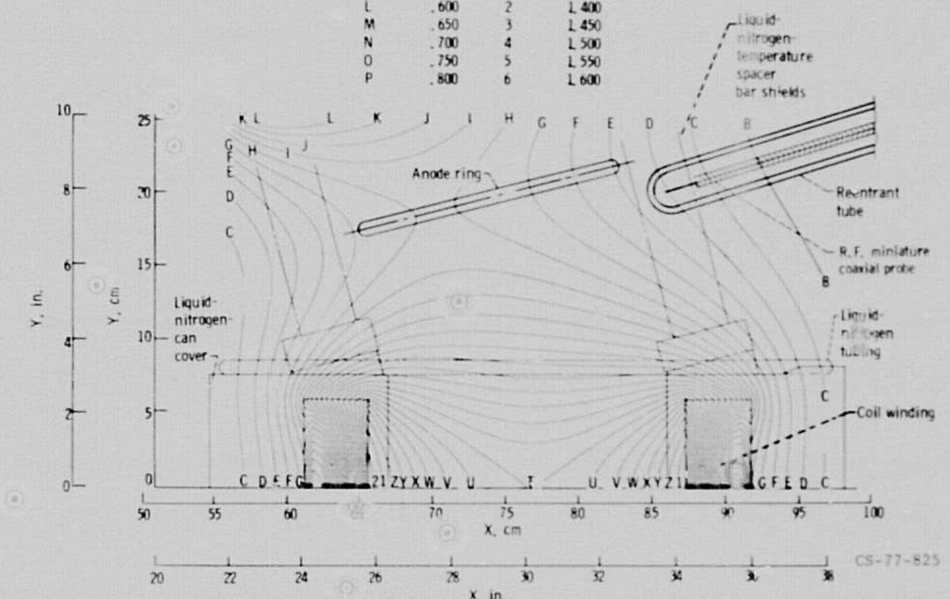

Figure 3. - Location of re-entrant tube - RF probe assembly with respect to the anode ring and coil dewars in port 8. Active tip of probe is 1.5 cm adjacent to the anode ring and 5 - 9 cms away from it. Magnetic field strength at probe tip is 20% of B_{max}.

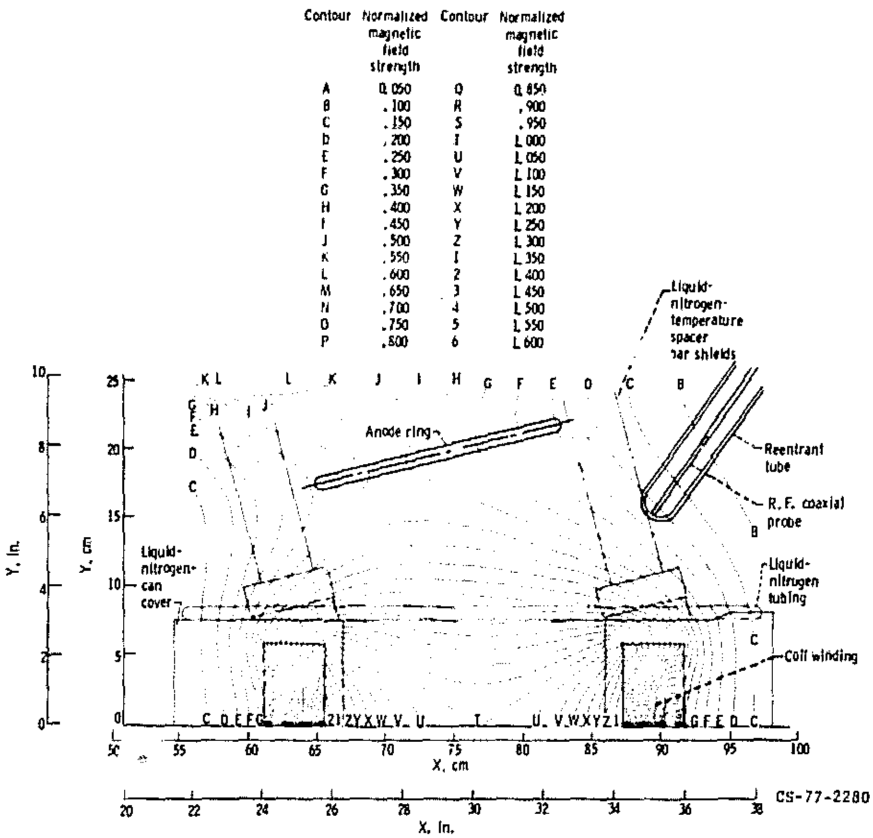

Figure 4. - Location of RF probe with respect to the anode ring and coil dewars in port 2. Magnetic field strength at probe tip is 20% of B_{max}.

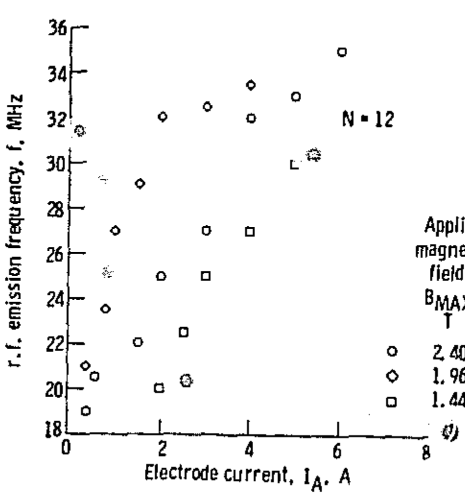

Figure 5. - Frequency of moving peaks as a function of of the anode current for different values of the d.c. magnetic field. Twelve negative midplane electrode rings, max. magnetic field strength B_{max} = 2.4 tesla. Background neutral gas pressure = 5.3×10^{-5} torr. Neutral particles/cm^3 = 17×10^{11}.

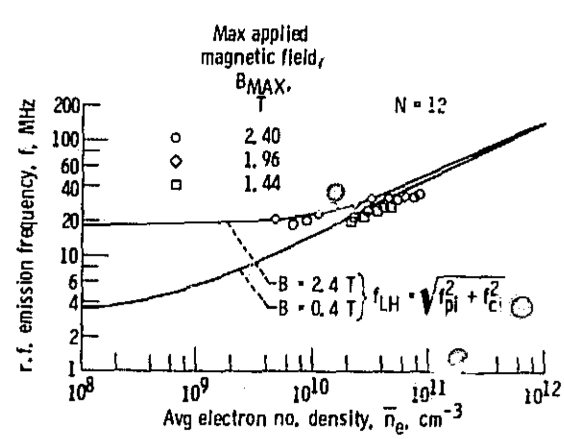

Figure 6. - Frequency of moving peaks as a function of the average electron number density and maximum applied magnetic field. Twelve negative electrode rings. Also shown in the figure are curves described by the cold plasma lower hybrid resonance for B = 2.4 tesla and 0.4 tesla. Background neutral gas pressure = 5.3×10^{-5} torr. Neutral particles/cm^3 = 17×10^{11}.

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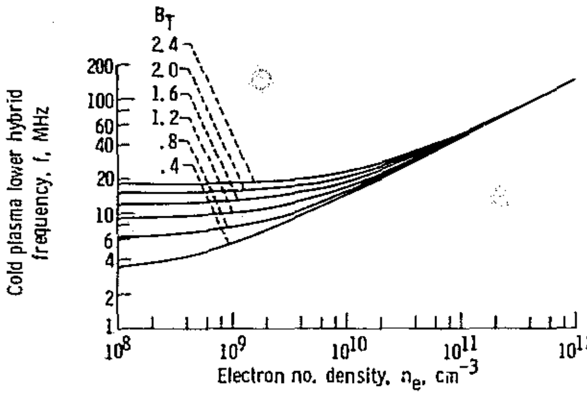

Figure 7. - Plot of cold plasma lower hybrid frequency vs. the electron number density for different values of the d.c. magnetic field for atomic deuterium.

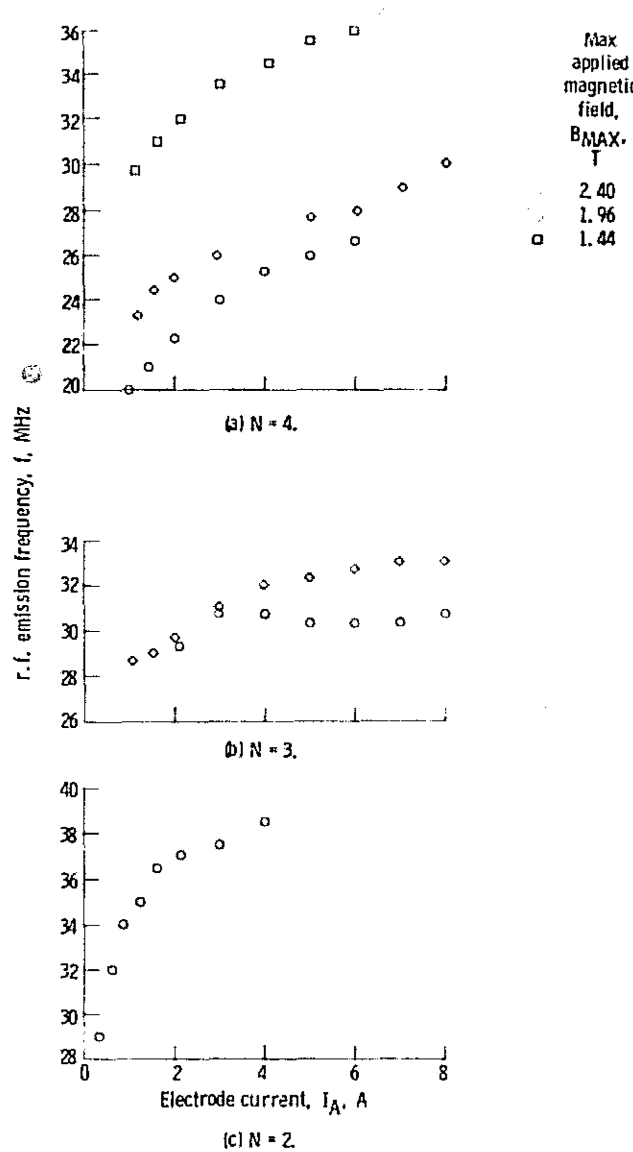

Figure 8. - Frequency of moving peaks as a function of the anode current for different values of the d.c. magnetic field. Max. magnetic field strength = 2.4 tesla. Negative polarities and different electrode configurations (N). Background neutral gas pressure = 5.3×10^{-5} torr. Neutral particles/cm^3 = 17×10^{11}.

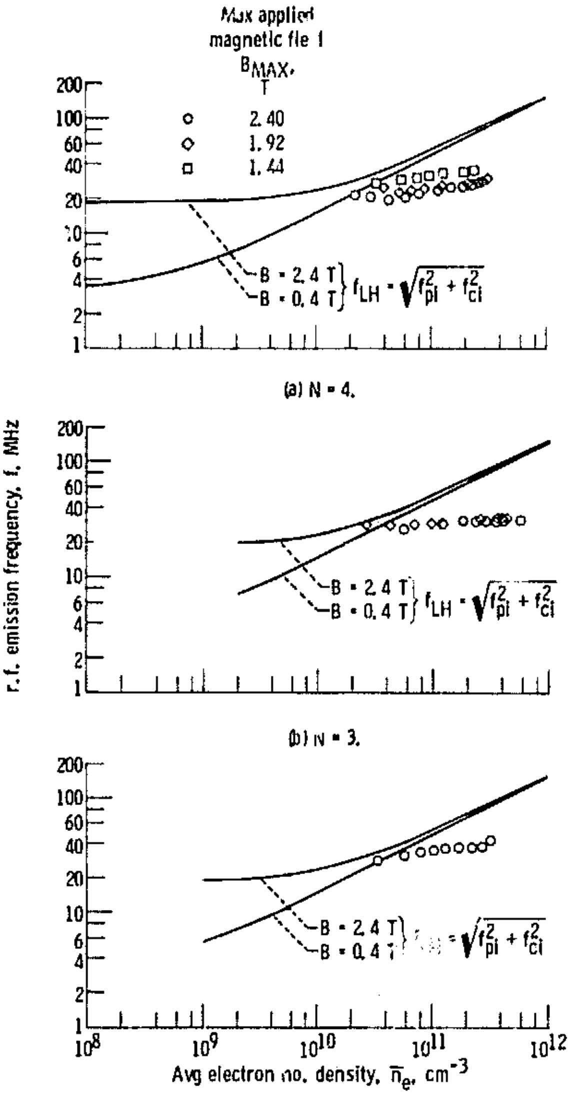

Figure 9. - Frequency of moving peaks as a function of the average electron number density and maximum applied magnetic field. Negative polarities and different electrode configurations (N). Shown in the figures are the curves described by the cold plasma lower hybrid resonance for B = 2.4 tesla and 0.4 tesla. Background neutral gas pressure = 5.3×10^{-5} torr. Neutral particles/cm^3 = 17×10^{11}.

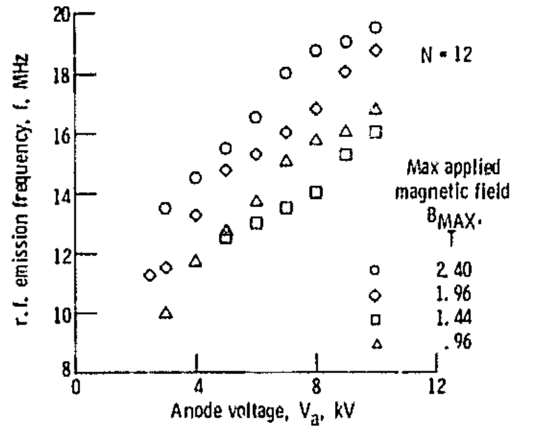

Figure 10. - Frequency of moving peaks as a function of electrode voltage for different values of the applied magnetic field. Twelve positive midplane electrode rings, max. magnetic field strength B_{max} = 2.4 tesla. Background neutral gas pressure = 5.3×10^{-5} torr. Neutral particles/cm^3 = 17×10^{11}.

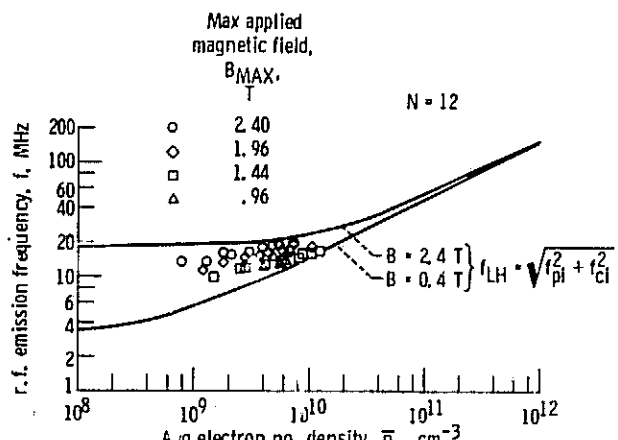

Figure 11. - Frequency of moving peaks as a function of the average electron number density and the maximum applied magnetic field. Twelve positive midplane electrode rings. Also shown in the figure are curves described by the cold plasma lower hybrid resonance for B = 2.4 T and 0.4 T. Background neutral gas pressure = 5.3×10^{-5} torr. Neutral particles/cm^3 = 17×10^{11}.

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Contour	Normalized magnetic field strength	Contour	Normalized magnetic field strength
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C	.150	S	.950
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E	.250	U	1.050
F	.300	V	1.100
G	.350	W	1.150
H	.400	X	1.200
I	.450	Y	1.250
J	.500	Z	1.300
K	.550	1	1.350
L	.600	2	1.400
M	.650	3	1.450
N	.700	4	1.500
O	.750	5	1.550
P	.800	6	1.600

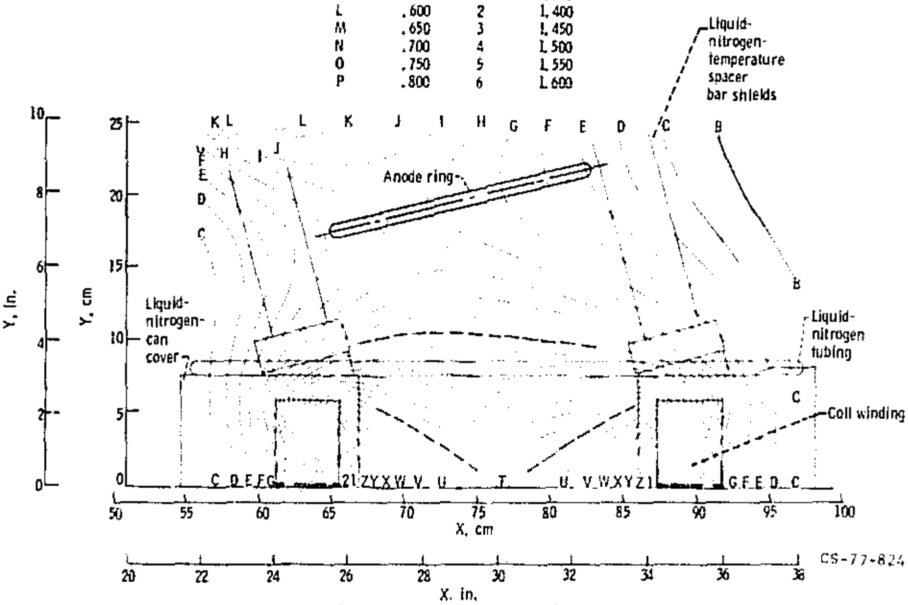

Figure 12. - Approximate geometric location of the lower hybrid emitting region. Dotted lines indicate upper and lower limit of the magnetic field strength variation in the emitting region for an applied maximum magnetic field of 2.4 T.