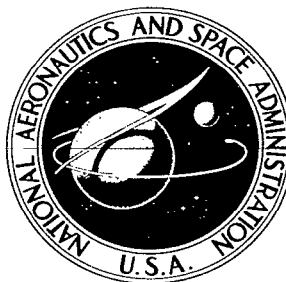


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CYCLOTRON WAVES IN A COLLISIONLESS PLASMA*

by C. B. Wharton and J. H. Malmberg
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SUMMARY

Experimental studies of plasma waves in a 2 meter long collisionless plasma column, over the frequency range 30 to 520 Mhz, are reported. Special attention is given to the frequencies neighboring the electron cyclotron frequency ω_b . At least three (and perhaps more) distinct waves having resonances at or near ω_b are found. Two waves lie above the cyclotron frequency. One has a velocity greater than that of light and is a forward wave, apparently an electromagnetic waveguide mode, perturbed by the plasma. The other is a slow, backward wave, having a propagation cutoff at the upper hybrid frequency $\omega_{uh} = (\omega_b^2 + \omega_p^2)^{1/2}$, with a dispersion curve resembling that of the C_{01} cyclotron wave. This wave is heavily damped in space, typically 10 to 20 dB per wavelength. The third wave is a slow forward wave, lying below ω_b and resembling a whistler. It is only moderately damped.

The measured dispersion curves of these waves are presented, and their relation to the predictions of theory is discussed.

INTRODUCTION

A plasma column confined by a magnetic field inside a conducting cylinder can support many modes of waves, both electrostatic and electromagnetic. The theory of electron plasma oscillations, ion sound waves, Alfvén waves, whistlers and the ordinary and extraordinary modes of electromagnetic wave propagation, for many different combinations of parameters such as magnetic field strength and plasma density, have been considered in the literature, and excellent reviews of this work have been published (refs. 1, 2, 3, 4). However, detailed experimental confirmation of the theories is lacking in most cases. We have previously reported results on the dispersion and collisionless damping of longitudinal plasma waves (refs. 5, 6). We report here measurements of the dispersion relations of waves near the electron cyclotron frequency. Because the cyclotron wave is highly dispersive, with wavelengths varying from meters to centimeters over a small frequency range (or density change, for fixed-frequency), a long, very stable, quiet plasma was required for these measurements. This apparatus is discussed in the section below and in reference 12.

Growth and damping of spacecharge waves are easily seen qualitatively in our wave experiments. However, there are several waves propagating simultaneously at some frequencies, which makes quantitative measurements difficult. We have not yet been successful in identifying some of the wave types, but for most

* The work described in this Contractor Report will be reported at the Seventh International Conference on Phenomena in Ionized Gases, Beograd, Yugoslavia, and will be published in the proceedings of that conference.

waves, the measured dispersion fits the theory in the vicinity of the electron cyclotron frequency. The wavelengths measured are long, yet the waves are heavily damped. In a collisionless plasma, such as in the experiment discussed here, collisional damping is not important; however, there may be Landau damping. The waves observed near the cyclotron frequency consist of cyclotron plasma waves, evanescent waves, and electromagnetic waves mixed together. Further, when an electron beam is injected, certain cyclotron waves are observed to increase in amplitude and others to decrease. Whether this is due to wave growth and damping or to variations in probe coupling caused by the beam, has yet to be determined. If the increase in amplitude is really due to wave growth, the effects may be understandable in terms of the theory of microinstabilities (refs. 7, 8, 9, 10, 11).

EXPERIMENTAL DETAILS

These investigations used the same apparatus as used for the research reported in references 5 and 12 with the addition of a 10 cm I.D. stainless steel pipe surrounding the plasma, to cut off electromagnetic wave coupling between the probes, and an insulating ring between the duoplasmatron and the main chamber, to permit a voltage difference to be applied between the duoplasmatron anode and the grounded pipe. A general view of the equipment is shown in Fig. 1. Four movable probes are guided by rails in the vacuum chamber and controlled externally by manipulators seen in the left of the picture. The probes are able to explore any region along the chamber, inside a 10 cm radius when the liner pipe is absent. When the slotted liner is in place, their angular variation is restricted by the slot width to about 10° , allowing only a slice of the column to be explored. The probes can be retracted radially completely out of the plasma.

The plasma density in the chamber near the duoplasmatron source is typically between 5×10^7 and $5 \times 10^9 \text{ cm}^{-3}$ for these experiments and is steady state. The density decreases downstream along the axis due to radial diffusion, producing a 25% drop from one end to the other. The radial density profile as indicated by the saturation ion current to a small Langmuir probe is given in Fig. 2. The plasma spatial potential profile may be inferred from the probe floating potential, also given in Fig. 2. The center of the column is about 15 volts positive with respect to the wall for these experimental conditions. The potential on axis is about $(V_A - 3kT)$, where V_A is the voltage applied to the anode of the plasma source and T is the electron temperature. We have observed that, when the axial potential is below about 10 volts, a rotational instability is excited. The rotational frequency is between 20 and 60 kc., depending on density, magnetic field strength and axial potential. As the duoplasmatron anode bias voltage is raised, the rotation ceases and the plasma noise, as picked up by probes, drops to a low level. Further increase in the bias voltage leads to a rotation in the opposite direction at a frequency of 50 to 100 kc. accompanied by a decrease in density. This effect will be described in more detail elsewhere. The profile of Fig. 2 was obtained in the "stable" condition. The profile is broader or even double-peaked when the column instability is present. When the column is rotating, a modulation of the transmitted waves and R.F. noise at the rotation frequency is observed.

The electron temperature is determined by Langmuir probes and by energy-analysis of electrons escaping through a hole in the ion trap at the downstream end. The electron temperature varies between 6 and 12 eV for various adjustments of the machine parameters.

The R.F. transmission circuitry uses a conventional interferometer (ref. 4), with 5 kc. modulation on the carrier, and a tuned video amplifier and phase-coherent detector in the receiver, to reject noise outside the narrow pass-band. The crystal detector in the interferometer is operated at a high level (~ 0.5 mA) by keeping the CW reference signal level at about 1 mW. This gives an overall system sensitivity almost as high as that of a superheterodyne. This high sensitivity and large dynamic range are necessary to follow the waves over their damping range. High frequency fluctuations in the density of the plasma in the transmission path result in corresponding changes in wave number (since the transmitter frequency is fixed) which leads in turn to noisy modulation of the phase of the received signal. Since the interferometer averages the received signal over a comparatively long time, in extreme cases, this effect can destroy the interference fringes even where appreciable power is still received. We call this phenomena "phase scrambling". The signal is finally lost by "phase scrambling" rather than in the receiver-generated noise.

Plasma waves are launched and received with the same probes used for current and potential measurements. These probes tend to excite a spectrum of plasma modes, and because of their small size, have rather poor coupling. Planar grids were tried but led to a serious loss of density, as well as to severe standing waves.

In an attempt to improve the coupling of our probes to the cyclotron waves, we tried launching from a matched slow-wave helix surrounding the plasma in front of the suppressor grid. The signal transmission level increased ten-fold, but the resulting wave-dispersion (plotted as an ω - β , or Brillouin diagram in Fig. 3) showed evidence of the presence of an electron stream. The "beam" velocity, as determined by the slope of the phase curves $\Delta\omega/\Delta\beta$, depended on the helix voltage, leading to the conclusion that the electron stream was due to ion-generated secondary electrons being liberated from the helix. The secondary electron energies computed from electrode potentials are compatible with wave group velocity for all of the data. Figure 3 shows an asymmetry about $\beta = 0$. In the "downstream" sense (from plasma source toward ion trap) the normal plasma waves were found, but in the "upstream" sense two sets of waves were found, one corresponding to more-or-less normal waves, and the other corresponding to plasma oscillations and cyclotron oscillations drifting on the beam of secondary electrons. To further demonstrate the drift modes, we turned off the plasma and turned on an electron beam from the electron gun, leaving the magnetic field and wave probes as before. Only upstream propagation was found, but the beam modes were present as expected. In the plasma experiment using the helix, without the electron gun the "lower branch" line of the beam mode is seen to intersect the $\beta = 0$ axis at ≈ 3 Mc, suggesting that the plasma frequency of the beam of secondary electrons was about this value. The "upper branch" line passes through the cyclotron frequency f_p .

The effects of these beam-waves in the plasma can be eliminated by using the wire probes to launch the waves. This reduces the wave launching efficiency,

but also lowers the current of secondary electrons to a negligible level. Secondary electrons from the ion trap suppressor grid and from the probe wires are then a minor problem for wave propagation in the upstream direction only, leading to abnormal damping, and in some cases wave growth. Their current density is too low to cause oscillations however, and no effect on downstream propagation is evident.

The lower branch plasma waves qualitatively fit a dispersion relation appropriate to the density profile sketched in Fig. 2. Further discussion of the dispersion is given in the section below and in reference 6.

CYCLOTRON WAVE OBSERVATIONS

At least three (and perhaps more) distinct waves having resonances (wave-number becoming large) or cutoffs near the electron cyclotron frequency have been catalogued. Since two or three waves are present simultaneously at certain frequencies, we have had to develop rather sophisticated techniques to analyze the interferometer recordings. When two waves having widely different wavelengths are present, the analysis is straightforward. When the wavelengths are within a factor of 2 of each other, however, several measurements at closely spaced frequencies are required to follow the dispersion of the individual waves.

Two waves lie above the cyclotron frequency. One has a high phase velocity, ($v_\phi > c$), and is a forward wave. The other is a "slow wave", having a phase that retards with frequency, i.e., a backward wave. The fast wave apparently is an electromagnetic waveguide mode, perturbed by the plasma. The slow wave apparently is the C_{01} cyclotron wave (refs. 2, 4, 13, 14) having a propagation cutoff at the upper hybrid frequency, $f_{uh} = (f_b^2 + f_p^2)^{1/2}$. It is heavily damped at wavelengths shorter than about 8 cm and we have not yet been successful in plotting out the entire dispersion curve. Partial dispersion curves are shown in Figs. 4, 5, and 6. Only the "downstream" half of the ω - β diagrams are plotted. The "upstream" half looks similar, except for possible streaming effects of secondary electrons.

Below the cyclotron frequency there appear to be several waves. The fastest of these, fairly certainly, is a plasma perturbed TE_{mn} waveguide mode, mentioned above. Its dispersion curve matches that for a TE_{11} mode in a waveguide whose cross-section is 1/10 filled with plasma. The plasma density distribution shown in Fig. 2, inside a 10 cm diameter tube, gives a reasonable fit. The dispersion for this wave is very similar to that for a whistler (refs. 4, 15).

The other "cyclotron waves" have not been identified, but are strong waves, having only moderate damping. One of them, shown in Fig. 5, having a cutoff frequency between 200 and 300 Mc, seems to be a wave pair, with a frequency-separation depending on density. If so, it should exhibit Faraday rotation. The "whistler" mentioned above would also have Faraday rotation, except that the ordinary wave component is cut off by the waveguide cutoff, leaving only the elliptically polarized extraordinary component. No evidence for polarization rotation of these waves has been found in our experiment.

The "lower branch" waves--the conventional space charge or electron acoustic waves of a warm, finite plasma column--have been extensively investigated at General Atomic and elsewhere, and reported on in the literature (refs. 2, 5, 13). We have plotted the measured dispersion curves here, since we use these waves in a diagnostic manner, to aid us in understanding the cyclotron wave characteristics, and to determine the plasma density.

Figures 4, 5, and 6 show effects of various plasma densities and cyclotron frequencies on the cyclotron family of waves. The resonances and cutoffs of the waves move in the expected manner as the plasma and cyclotron frequencies are adjusted.

The above results were obtained using pure H_2 gas in the duoplasmatron. The waves were also investigated using a mixture of hydrogen and helium in the source. The pressure and mixture were adjusted empirically to obtain the same wavelength at some particular frequency as observed using pure hydrogen as a source gas. When this was done the damping length at that frequency did not change appreciably, but the signal-to-noise ratio was much improved, allowing waves to be observed at shorter wavelengths than before. The fluctuations in D.C. probe current were decreased by a large factor. The reduction in phase scrambling with the He- H_2 mixture permitted wavelengths as short as 6 cm to be observed just above the cyclotron frequency.

With the H_2 -He mixture the adjustment of the duoplasmatron anode bias voltage is less critical than with pure H_2 , to achieve the stable column condition in the previous section. In the unstable condition, the cyclotron waves have a small amplitude modulation imposed, but the time-averaged data looks similar to that obtained when the column was stable. This is not true with the "lower branch" spacecharge waves, whose short-wavelength characteristics are very much altered in some cases when the rotational instability is present.

General Atomic Division of General Dynamics Corporation
San Diego, California, July 23, 1965

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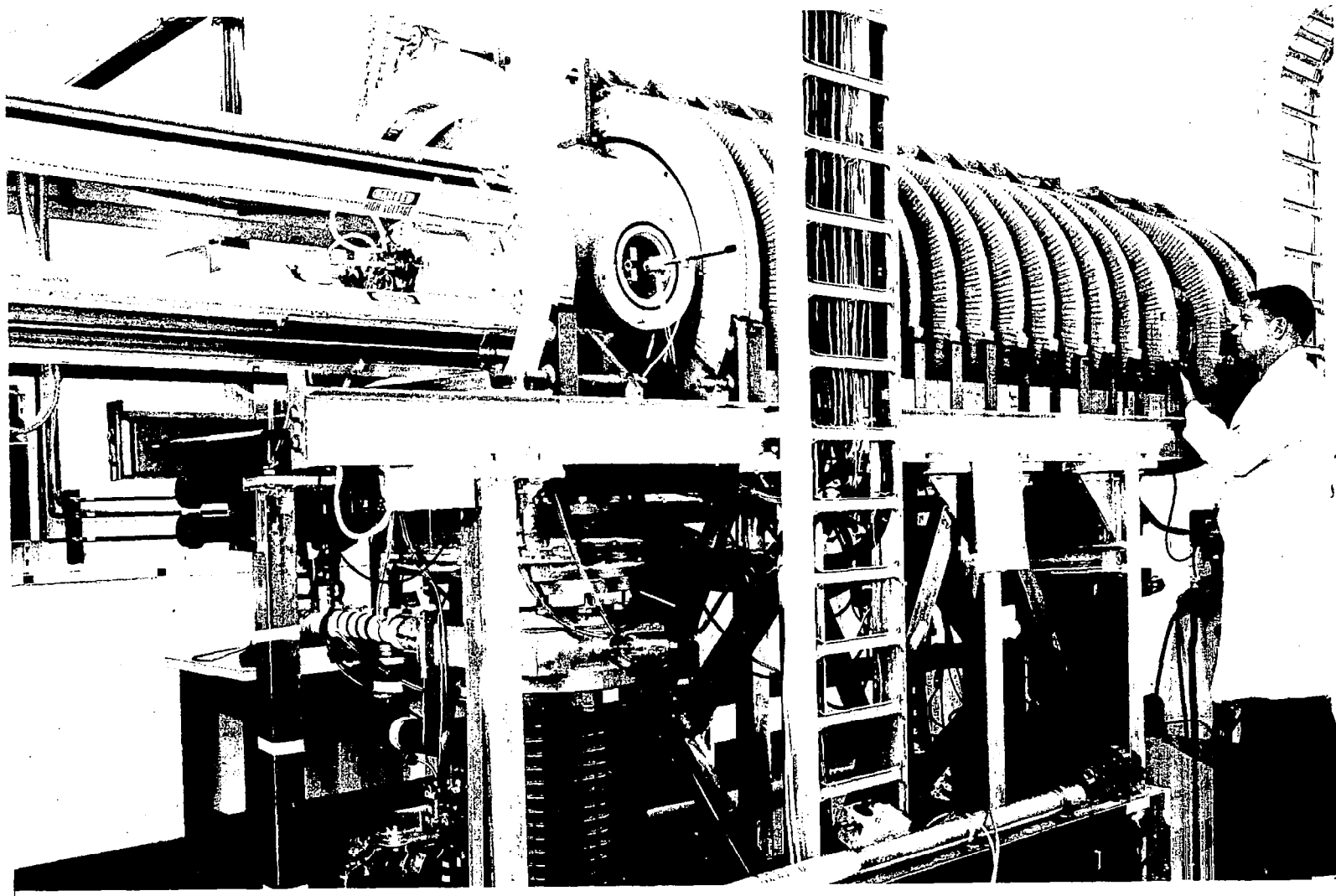


Figure 1. Photograph of the apparatus used for studies of waves in the steady-state collisionless plasma. The solenoidal field is uniform to $\pm 1\%$ along the length. At far left are carriages for movable probes. The plasma source is mounted on the left end of the vacuum chamber and the electron gun on the right end. (Not visible.)

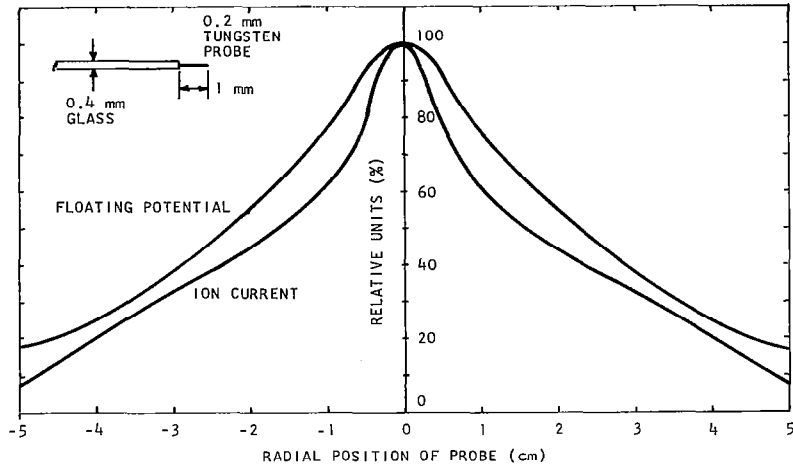


Figure 2. Profile measurements of floating potential and saturation ion current, obtained by a small Langmuir probe. 100% refers to +16 volts and +6 amperes, respectively for these curves.

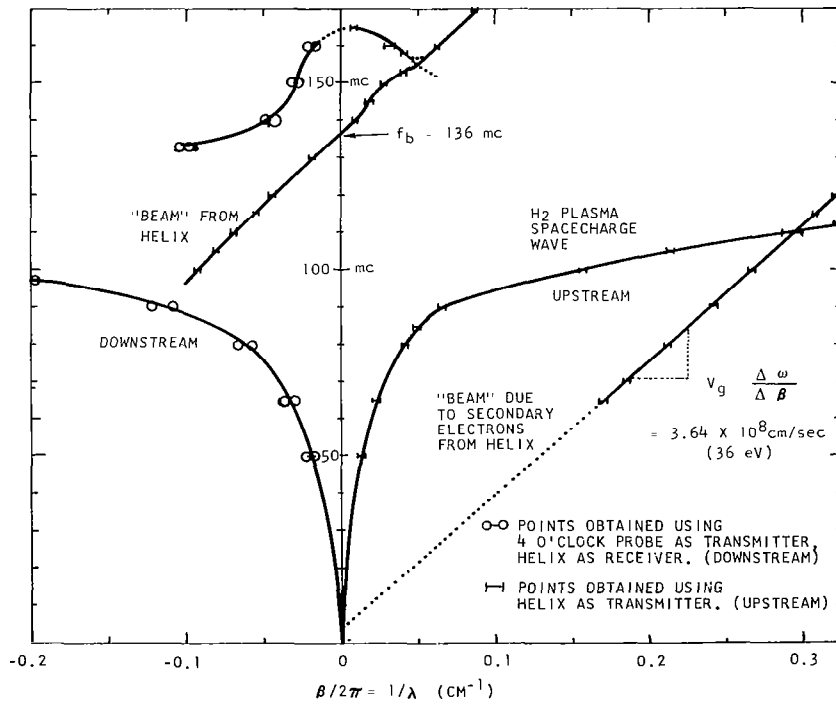


Figure 3. Brillouin(ω - β) diagram for waves in the collisionless H_2 plasma, over the frequency range 0 to 170 Mc. The waves launched by a helix (upstream) show evidence of an electron stream, due to secondary electrons off the helix. The cyclotron frequency f_b was 136 Mc.

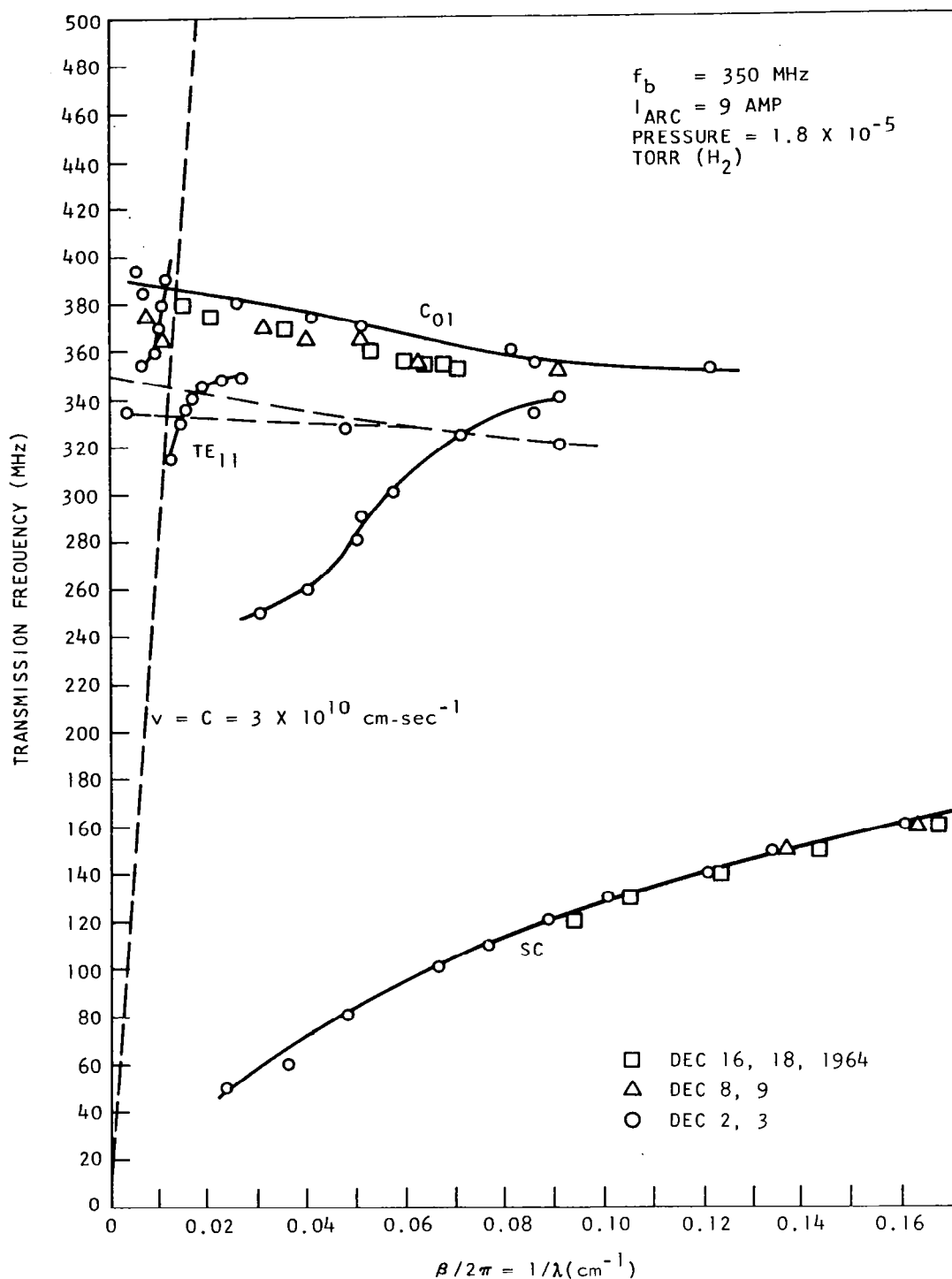


Figure 4. ω - β diagrams for cyclotron waves in the collisionless H_2 plasma, over the frequency range 0-500 Mc. Cyclotron frequency f_b was 350 Mc and plasma density n_e was approximately $4.2 \times 10^8 \text{ cm}^{-3}$. A portion of the curve for the longitudinal spacecharge waves is also shown. The waves were launched and received by small wire probes.

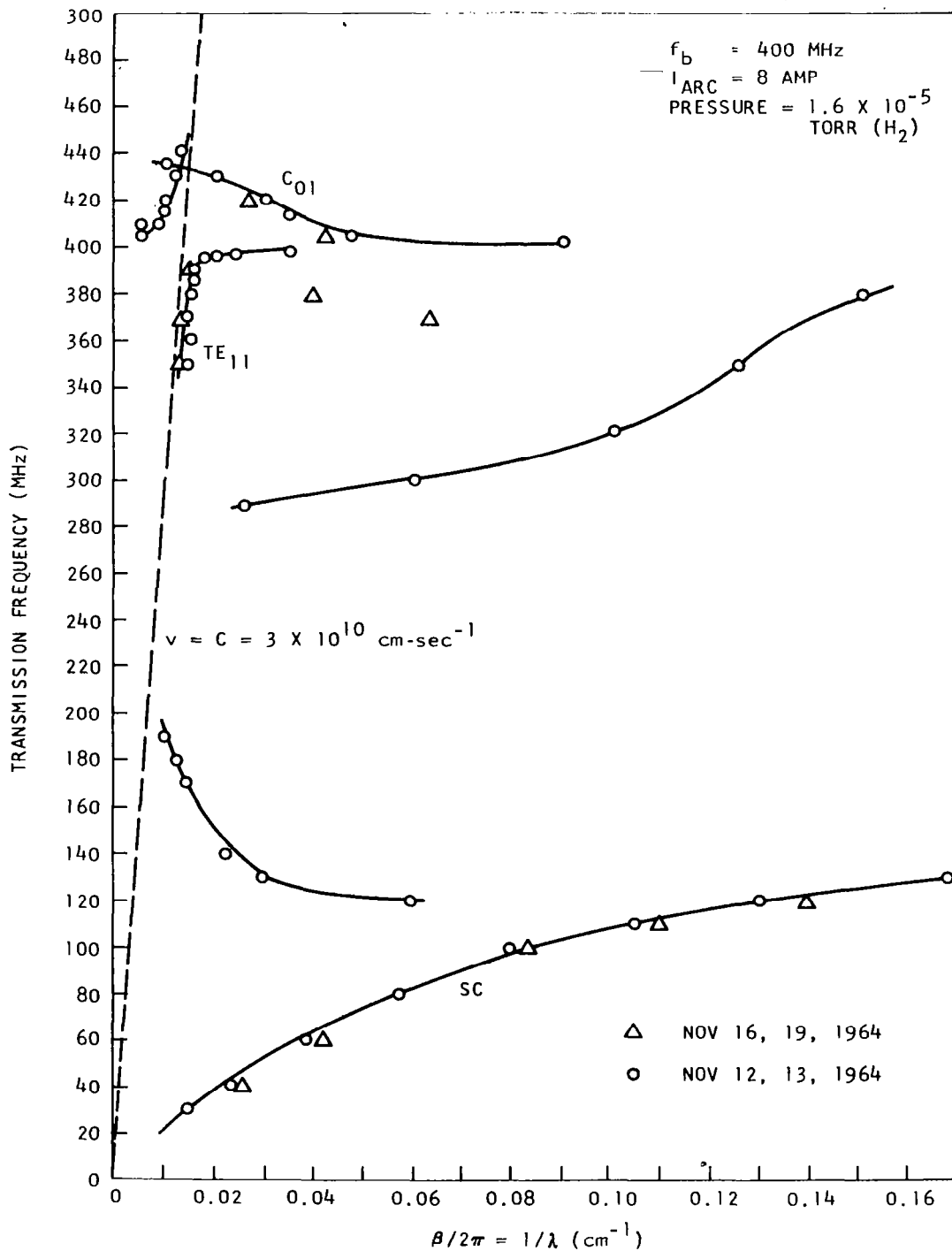


Figure 5. ω - β diagrams as in Fig. 4, but $f_b = 400 \text{ Mc}$, $n_e \approx 3.9 \times 10^8 \text{ cm}^{-3}$.

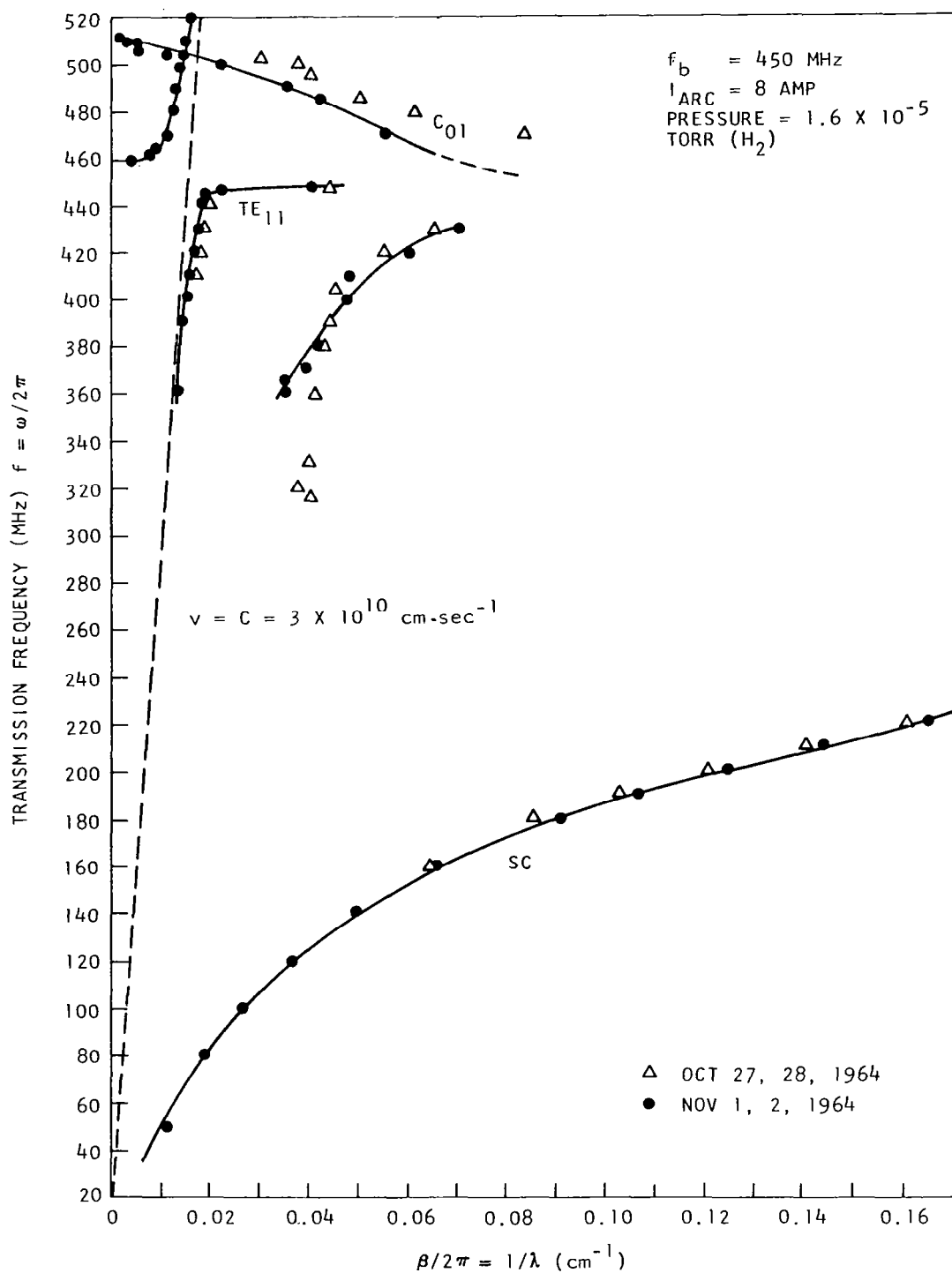


Figure 6. ω - β diagrams as in Fig. 4, but $f_b = 450 \text{ Mc}$, $n_e \approx 7.1 \times 10^8 \text{ cm}^{-3}$.