TRAVELLING WAVE INTERACTION IN PLASMAS

G. D. BOYD* and R. W. GOULD
California Institute of Technology, Pasadena, California

Abstract—Interaction between a slow space charge wave which travels along a cylindrical plasma column and an electron beam which passes down the axis of the column is demonstrated experimentally. A spatially growing wave exists when the velocity of the beam is approximately equal to the velocity of the unperturbed wave.

It has been shown by a number of investigators that a plasma column of finite radius supports a space charge or 'electrostatic' wave which travels along the column with a phase velocity which, under suitable conditions, can be made to be only a few hundredths of the velocity of light.† This wave propagates at frequencies well below the electron plasma frequency, \( \omega_p \), and has an upper cut-off at \( \omega = \omega_p/\sqrt{1 + K} \), where \( K \) is the dielectric constant of the material (glass or vacuum) immediately surrounding the plasma column. Because this wave has a strong longitudinal component of electric field, an electron beam travelling down the axis of the column should interact strongly with the wave when the electrons travel at approximately the same speed as the wave (GOULD and TRIVELPIECE, 1958). Electrons are bunched by the field of the wave and the bunches in turn reinforce the wave. The amplitude of the wave grows as it progresses down the plasma column. This is precisely the travelling wave tube interaction except that the radio frequency fields acting on the electron beam are those of the plasma wave instead of those of a wave travelling along a helical conductor. The theory of travelling wave interaction (PIERCE, 1950) may therefore be applied to calculate the rate of spatial growth.

This paper reports the results of an experiment designed to verify this interaction in a cylindrical plasma column. A schematic drawing of the tube used is shown in Fig. 1. The plasma is generated by an arc discharge in mercury vapour and the positive column of the discharge is used for the plasma interaction region. The arc cathode on the right is the source of plasma electrons. The electron gun on the left produces a beam which is collected by the beam collector on the right. Modulation at a frequency of 490 Mc is introduced on the electron beam by means of the input cavity resonator on the left. Currents in the beam and in the plasma induce the signal in the output cavity resonator on the right. In addition, a travelling radio frequency probe (not shown in the figure) which could be moved along the interaction region, was used to determine how the wave amplitude varied along the column.

Fig. 2 shows the nature of the results which were obtained. The oscilloscope traces (above) show the output signal as a function of current in the arc discharge. In a low pressure discharge the electron density is proportional to discharge current, hence the abscissa of these traces is proportional to the square of the electron plasma frequency in the interaction region. The oscilloscope traces show that for each beam voltage there is a plasma density which produces a greatly increased output signal. At this point the plasma electron density is such that the velocity of the wave which travels along the column is approximately equal to the beam velocity. It may be seen from the sequence of traces that as the beam velocity is increased by increasing the accelerating potential, the density required for velocity synchronism increases. From this and similar data the dispersion characteristic of the plasma wave can be determined in the manner described below.

Traces in the lower half of Fig. 2 show the variation
in signal amplitude along the tube, as measured by the travelling radio frequency probe. In each trace the discharge current has been adjusted so as to produce the maximum signal in the output cavity resonator. In the first two traces growth of the signal is apparent as the wave propagates to the right. The periodic variations in the amplitude are due to the interference with the wave which is reflected from the output cavity resonator. The spatial periodicity of the variations is a half wavelength of the plasma wave and clearly increases as the velocity of the wave is increased (corresponding to increased beam potential in these traces). The third trace is a double one, the lower of the two traces being obtained with the electron beam off. The attenuation of the wave which is observed there is due to collisions of the plasma electrons with ions, neutral molecules and the wall of the discharge tube. Introduction of the electron beam (upper trace) reduces the attenuation but the interaction is not sufficiently strong to produce much growth.

The data of Fig. 2 and other similar data has been used to construct the dispersion characteristic of the space charge wave of the cylindrical plasma column. Assuming that the maximum output corresponds to velocity synchronism between the wave and the beam one then knows both the frequency of the wave \( f = \omega / 2\pi \) and the velocity (calculated from the accelerating potential of the electron beam, \( v = \sqrt{2eV/m} \)). The axial wave number is then obtained from the relation \( \beta = \omega / c \). The result of a number of measurements with different accelerating voltages is shown in Fig. 3 along with the theoretical result of Trivelpiece and Gould (1959), (solid line). The electron plasma frequency \( f_p = \omega_p / 2\pi \), was measured independently by the cavity perturbation technique (Biondi and Brown, 1949). The two rather distinct sets of data were obtained with different adjustments of the various electrode potentials. The difference between the two data reflects the fact that the constant of proportionality between electron density and discharge current depends slightly upon electrode potentials, whereas the same constant was actually employed in calculating \( f / f_p \) for the two runs.

Also shown in Fig. 3 is the interaction at plasma resonance \( (f = f_p) \) of the type which has previously been reported (1958). As in the travelling wave interaction at lower values of \( f / f_p \), a pronounced increase in the signal level at the output cavity resonator is observed. Although the radio frequency fields outside the plasma are very weak, it has also been possible to confirm that this increase in output corresponds to a spatially growing wave. The interaction between an electron beam and a plasma medium at plasma resonance is essentially the one described by Bohm and Gross (1949a, 1949b and 1950) and others, though an extension of the one-dimensional theory is necessary to account for the finite beam diameter.

Acknowledgements—It is a pleasure to acknowledge valuable discussions with L. M. Field, A. W. Trivelpiece and D. G. Dow and the support of the United States Navy Office of Naval Research in conducting this investigation.

REFERENCES