Excitation of Plasma Oscillations and Growing Plasma Waves


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Recent work in our laboratory has been concerned with the experimental verification of plasma interaction theories which predict spatially growing waves in a plasma which is traversed by a beam of fast-charged particles. The growing wave results from the excitation of oscillations of the plasma electrons by the beam and the interaction of the oscillating electrons back on the beam. The wave amplitude increases exponentially with distance along the beam. The rate of growth for a constant excitation frequency \( \omega \), is predicted to be zero for low plasma frequencies, to rise sharply when the plasma frequency \( \omega_p = (ne^2/\varepsilon_0 m)^{1/2} \) approaches the excitation frequency, and to fall monotonically as the plasma frequency increases further.

Previous methods employed to excite plasma oscillations with a directed beam have been described in the literature as unsuccessful. This communication describes preliminary results of a new experiment in which the beam is modulated by a microwave signal before it interacts with the plasma. A very strong interaction is observed which shows essentially the theoretically predicted form of behavior.

A 400-volt electron beam is passed along the axis of the positive column of a mercury arc discharge 1 cm in diameter (pressure \( 2 \times 10^{-4} \) mm Hg) as shown in Fig. 1. Before entering the plasma interaction region the electron beam is modulated with a short helix which propagates a slow electromagnetic wave with about the same velocity as the electron beam. The beam then passes along the axis of the arc discharge for a distance of five centimeters. Upon leaving the plasma-interaction region the modulated beam induces a microwave signal on the second helix which is then coupled into the output guide. This signal is detected, filtered with a 1000-cps low-pass filter, and presented on an oscilloscope. When the arc current is swept at 60 cps, displays of power output versus arc current, such as shown in Fig. 2, are obtained. Without filtering, the detected output is modulated about 30% with noise whose spectrum appears to be peaked at around 10 kc/sec. This noise, which vanishes when the input signal is removed, appears to be correlated with density fluctuations associated with moving striations.

Curves similar to those of Fig. 2 are obtained at other frequencies and the arc current for maximum output is indeed found to vary as the square of the modulating frequency over the range 2.2 to 4.0 Mc/sec. Measured values are observed to have a small finite intercept related to the contribution to the arc plasma density by the electron beam. Few low-pressure arcs such as ours, the electron density, and hence \( \omega_p \), is proportional to the arc current. Hence we obtain an experimental verification that the maximum rate of growth occurs when the plasma frequency is linearly related to the modulation frequency. While this experiment could be interpreted as a direct measurement of the electron
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Figure 3. Estimated plasma frequency versus arc current: G, from growing-wave experiment; S₁, minor peak of scattering experiment; S₂, major peak of scattering experiment; P, compilation of probe measurements (from reference 8).

density, it is essential in order to verify the theory that the electron density must be measured by another method. This could be accomplished with a Langmuir probe but we chose an alternative microwave method.

The arc column was inserted in a rectangular $TE_{10}$ wave guide so that the axis of the column was perpendicular to both the electric field and the direction of propagation. When the reflection coefficient of the column is plotted versus arc current at a fixed frequency, two distinct maxima are found. Double peaks have been observed previously, but not as yet explained. The elementary theory predicts only a single resonance at $\omega_R^2/\omega^2 = 2$ (modulated by a straightforward correction for the glass walls of the column, giving $\omega_R^2/\omega^2 = 2.81$ in this case). It can be shown that with a monotonic density variation radially, reflection should occur at nearly the average density.

Figure 3 is a plot of frequency squared versus arc current based on three types of data. The curve labeled P represents data taken from a compilation of probe measurements in mercury arc discharges and gives an average $\omega_R^2$ versus $I_A$ if one assumes a uniform plasma distribution throughout the cross section. Curves $S_1$ and $S_2$ represent an estimate of $\omega_R^2$ average versus $I_A$ based on the wave reflection experiments and obtained by dividing the measured arc current at a given incident frequency, by the reduction factor 2.81. $S_1$ and $S_2$ represent the major and minor peaks of the reflection coefficient, respectively. It appears likely that the major scattering peak, $S_1$, corresponds to the elementary theory. Curve G is from the growing-wave experiments, relates to the density on the axis of the arc, and is a plot of $\omega_R^2$ versus $I_A$ for maximum rate of growth. The appreciable discrepancy between the densities indicated by these three methods may possibly be accounted for by radial density variation in the plasma. Work is continuing using the high spatial and frequency resolution of this beam interaction method to attempt to solve the problem.

Variation of net gain with length and beam current, width of the peaked gain characteristic, and the effect of collisions and thermal velocity distribution on gain, from both theoretical and measured points of view, are being studied and will be reported on in a more detailed article.

It is felt that this amplification experiment verifies previous theoretical efforts of many workers in the field by producing a direct correlation between modulation and plasma frequency as well as demonstrating the laboratory existence of growing plasma waves such as have been postulated as one of many possible sources of solar and other radio astronomical noise. It is suggested that this mechanism may prove useful as a means of measuring radial variations in charge density in low-pressure gaseous discharges as well as other properties, such as characteristics of moving striations.

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