Figs. 2(d) and 2(e). The band width is clearly limited by the width of the microwave cavity and not by the crystal magnetic resonance width. Figure 2(f) is a display of the oscillation obtained by applying a small frequency modulation to the X-band klystron operating at a sufficiently high power level. Oscillation began at a pumping power of 9 mw.

The maser effect could be saturated by increasing the incoming L-band signal level (see Fig. 3). Practical interest lies, of course, in threshold signals where this limited power-handling capacity is not a serious disadvantage. Full details on the experiments in progress will be published at a later date. The assistance and advice of Mr. W. M. Walsh, Jr. is deeply appreciated.

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Excitation of Plasma Oscillations and Growing Plasma Waves*

G. D. Boyd, L. M. Field, and R. W. Gould
California Institute of Technology, Pasadena, California

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RECENT work in our laboratory has been concerned with the experimental verification of plasma interaction theories[1–3] 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 ω, is predicted to be zero for low plasma frequencies, to rise sharply when the plasma frequency $[\omega_p = (ne^2/\epsilon_0 m)^{\frac{1}{2}}]$ 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.[4] 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.

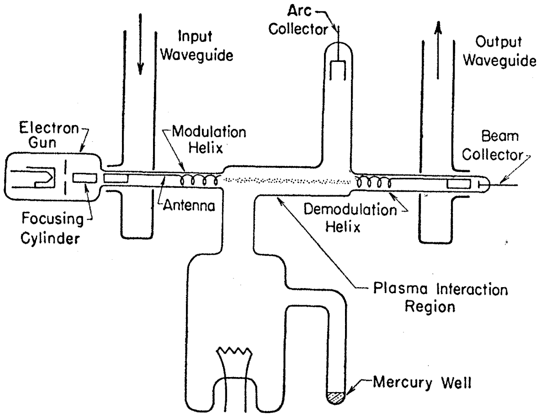

FIG. 1. Schematic drawing of plasma-beam tube used in growing-wave experiment.

A 400-volt electron beam is passed along the axis of the positive column of a mercury arc discharge 1 cm in diameter (pressure $= 2 \times 10^{-3}$ 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 wave 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.[5]

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 kMc/sec. Measured values are observed to have a small finite intercept related to the contribution to the arc plasma density by the electron beam. Fow low-pressure arcs such as ours, the electron density, and hence ω_p^2, is proportional to

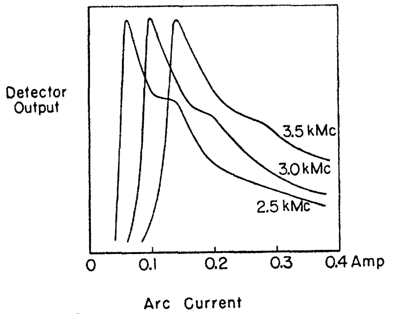

FIG. 2. Typical curves of signal output *versus* arc current for several modulating frequencies.

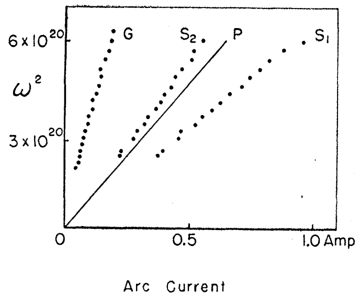

FIG. 3. Estimated plasma frequency *versus* arc current: G, from growing-wave experiment; S_2, minor peak of scattering experiment; S_1, major peak of scattering experiment; P, compilation of probe measurements (from reference 8).

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 density, it is essential in order to verify the theory that the electron density 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,[6,7] but not as yet explained. The elementary theory predicts only a single resonance at $\omega_p^2/\omega^2=2$ (modified by a straightforward correction for the glass walls of the column, giving $\omega_p^2/\omega^2=2.81$ 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[8] in mercury arc discharges and gives an average ω_p^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 ω_p^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 ω_p^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 resolve 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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Electron Resonances with Ultrasonic Waves in Copper*

R. W. MORSE, H. V. BOHM, AND J. D. GAVENDA

Department of Physics, Brown University,
Providence, Rhode Island

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At liquid helium temperatures the electron mean free path l in very pure metals may be considerably greater than the wavelength of readily attainable ultrasonic waves, in which case electron scattering becomes the dominant mechanism of attenuation of the wave. Consequently such measurements can give information about the electrons and, indeed, recently we have found that the attenuation in superconductors leads directly to the temperature dependence of the superconducting energy gap.[1]

The attenuation in the normal state depends on applied magnetic field. Bömmel first reported a minimum in attenuation with magnetic field in tin.[2] More recently we found a series of maxima and minima in an indium polycrystal[3] and reiterated the rather obvious suggestion made earlier[4] that these represent resonance conditions of orbit size to wavelength as the electrons move through the periodic fields associated with the