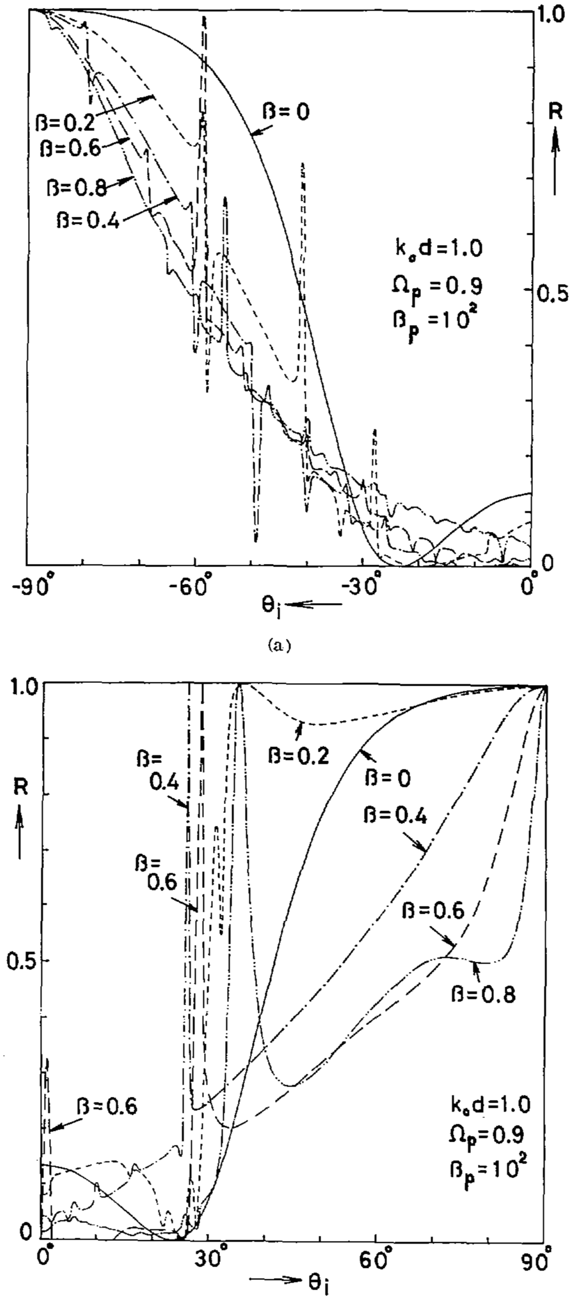

Fig. 2. Power reflection coefficient of plane electromagnetic wave obliquely incident upon moving compressible plasma slab for $k_0 d = 1.0$, $\Omega_p = 0.9$, $\beta_p^2 = 10^2$. (a) $\theta_i \geq 0°$. (b) $\theta_i \leq 0°$.

This limiting case agrees with the result obtained by Yeh [6]. He obtained the numerical result of the power reflection coefficient only for a case where H wave is normally incident upon the interface of the slab. We show the computational results of R_c versus θ_i for some selected values of Ω_p, $k_0 d$, and β in Fig. 1. Fig. 1 shows that, when β is not equal to zero, R_c becomes unity at a value of θ_i. This peak occurs at the values of θ_i and β which satisfy

$$\hat{\epsilon}_p' = 0 \tag{13}$$

in (7d). That is, in this case the angular frequency ω' in the rest frame of the slab satisfies the relation $\omega' = \omega_p'$. This phenomenon is well known as the term of plasma cutoff that is shown in CMA diagram [12]. Since ω' is shifted by the Doppler effect, it becomes a function of β, θ_i, and ω. Letting the angle θ_i at which (13) satisfies for given β, and Ω_p be θ_0, it is also shown that the value of θ_0 does not depend upon d. Consequently, even if the width of the slab is sufficiently small, it will be concluded that the incident wave can be perfectly reflected at θ_0. This physically unsatisfactory conclusion is derived from the assumption that the plasma considered here is collisionless. On the other hand, for $\theta_i < 0°$, R_c does not have any peaks for all the values of β.

For the case of $u_0' \neq 0$, we show the numerical results of R in Fig. 2 for $\beta_p = 10^2$ and the same values of $k_0 d$, Ω_p, and β as in Fig. 1. Fig. 2 shows that the same peaks as shown in Fig. 1 also exist at θ_0. For the range of $\theta_i > \theta_0$ the reflection coefficients become larger than that of the cold plasma slab case and for the range of $0° < \theta_i < \theta_0$ there exist several small peaks in R. For $-90° < \theta_i < 0°$ and $\beta \neq 0$ R has various peaks and oscillates rapidly for the variation of θ_i. These various peaks except one which occur at θ_0 do not appear, when the slab is stationary, i.e., $\beta = 0$ or the acoustic velocity in electron gas is zero, i.e., $u_0' = 0$. Hence we can come to a conclusion that the effects the movement of the slab has on the plasma waves excited in the compressible plasma slab make these various peaks occur. This conclusion can be shown from the following facts, i.e., the propagation constant α_e' of electromagnetic wave in (7b) does not depend on β, on the other hand that of plasma wave α_p' in (7c) involves the term of β, and since β_p^2 is generally very large and the scale of α_p' is mainly determined by the contribution from the first term in (7c), α_p' varies prominently for the small variations of β and θ_i.

Acknowledgment

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Probe-Triggered Audiofrequency Plasma Oscillations

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***Abstract*—Coherent sinusoidal oscillations have been observed in a magnetized dc gas discharge in neon. The oscillations have frequencies from 70 Hz to 7 kHz and are triggered by a small dc**

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bias on a wire probe immersed in the discharge. The oscillation period is proportional to the cube of the applied magnetic field and inversely proportional to the cube root of the discharge current.

I. Introduction

Audiofrequency oscillations in a magnetized RF discharge have been described and theoretically interpreted recently by Brooks and Pépin [1], whose paper contains a useful bibliography on low-frequency instabilities. Somewhat similar oscillations have been observed by Schmidt and Quinn [2] in a spherical dc cold-cathode discharge with a dipolar magnetic field. The present study is concerned with a uniformly magnetized dc discharge and examines experimentally the role played by a plasma-immersed wire probe which is dc biased to act as a generator of low-frequency oscillations. Such a study is relevant because the dc characteristics, RF impedance and transient response of biased probes (antennas) are widely used for plasma diagnostics in laboratory gas discharges and on rockets and satellites in the ionosphere. Bias-triggered instabilities could affect the accuracy of such diagnostic techniques and furthermore the bias could come not only from an external power supply or battery but also from satellite $\bar{v} \times \bar{B}$ induced voltages or from voltages produced by strong RF signal rectification in the plasma.

II. Experimental Apparatus

The discharge chamber shown in Fig. 1 is a sealed Pyrex glass tube containing high-purity neon at a pressure of approximately 70 μm Hg. Before backfill the tube had been baked for several hours and the backfill process included repeated ion-bombardment cleaning in neon of all probes and electrodes, each cleaning being followed by pumpdown and backfill. The anode and cathode are annular-grooved stainless steel discs, 7 cm in diameter and 15 cm apart. The probes are parallel tungsten wires 2 cm long, 0.010″ in diameter and separated by 2 mm. The probes lie in a plane normal to the tube axis and are 3 cm from the anode. The magnetic field is supplied by a four-section solenoid giving 15 G/A of coil current, as measured in the vicinity of the probes.

III. Results

Langmuir probe curves were taken but are difficult to interpret because of the magnetic field; the curves nevertheless exhibit the electron-saturation "knee" at around 1–2 V positive with respect to the anode. Whenever one of the probes was biased to some steady, positive threshold voltage in the vicinity of the Langmuir knee, a sinusoidal oscillation was detected at the other probe. As the bias was increased above threshold, the oscillation amplitude increased gradually, starting from zero; a typical waveform is shown in Fig. 2(a). A further increase in bias produced the distortion of Fig. 2(b) and a still further increase produced the marked distortion of Fig. 2(c). Beyond that point, greater positive bias produced broadband noise up to about 1 MHz. The remainder of this work is concerned only with the sinusoidal oscillations of Fig. 2(a).

The bias threshold for oscillation triggering varied from 1 V for high magnetic fields to about 5 V for low magnetic fields. A ringing effect seen in Fig. 3 resulted when the steady bias was set just below threshold and then was pulsed momentarily over the threshold. The ringing decay time increased as the steady bias approached the threshold value. With the steady bias higher than the threshold value, the resulting free oscillations could often be synchronized with repeated positive pulses superposed on the bias.

The variation of the oscillation period with magnetic field for a typical experiment is shown in Fig. 4. All of the lines have slopes very close to 3, indicating a cubic dependence of oscillation period on magnetic field for all values of discharge current shown. Also shown in Fig. 4 is the variation of oscillation period with discharge current; all the resulting lines have slopes very close to $-\frac{1}{3}$ indicating an inverse cube-root dependence. The planar theory of Brooks and Pépin [1] predicts a cubic variation with magnetic field and in

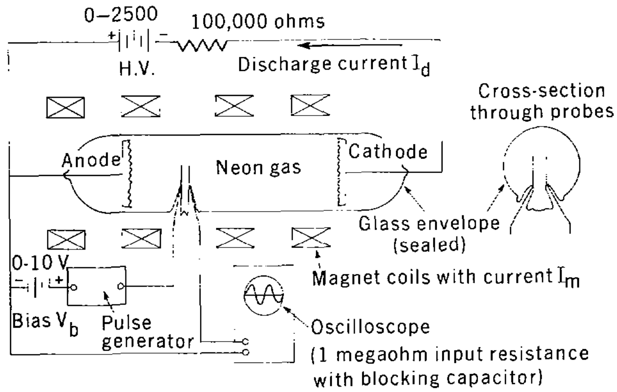


Fig. 1. Experimental apparatus.

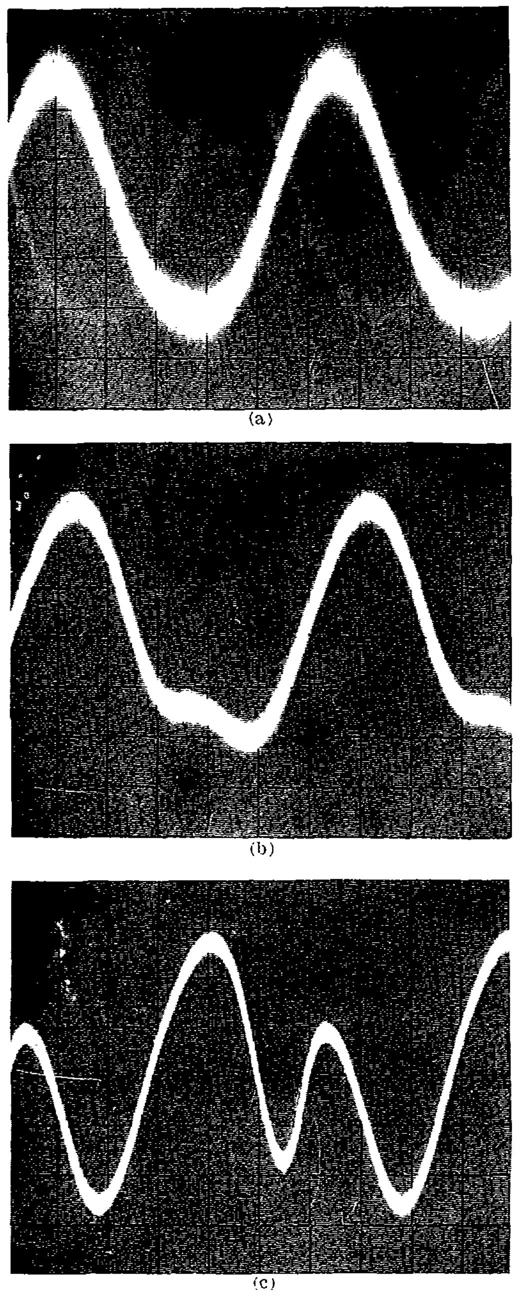
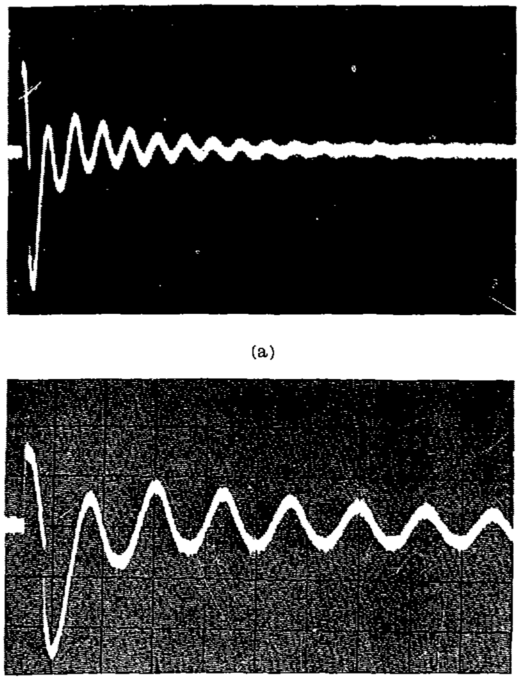


Fig. 2. Plasma oscillation waveforms: I_m = 15 A, I_d = 0.8 mA, and horizontal deflection of 0.5 ms per division. (a) With bias of 1.60 V and vertical sensitivity per division of 5 mV. (b) With bias of 1.65 V and vertical sensitivity per division of 10 mV. (c) With bias of 1.75 V and vertical sensitivity per division of 20 mV.



(a)

(b)

Fig. 3. Oscillation ringing: $I_m = 15$ A, $I_d = 0.8$ mA, vertical sensitivity of 20 mV per division, pulsewidth of 0.85 ms, and pulse level of 0.15 V. (a) With horizontal deflection per division of 5 ms and bias of 1.45 V. (b) With horizontal deflection per division of 2 ms and bias of 1.50 V.

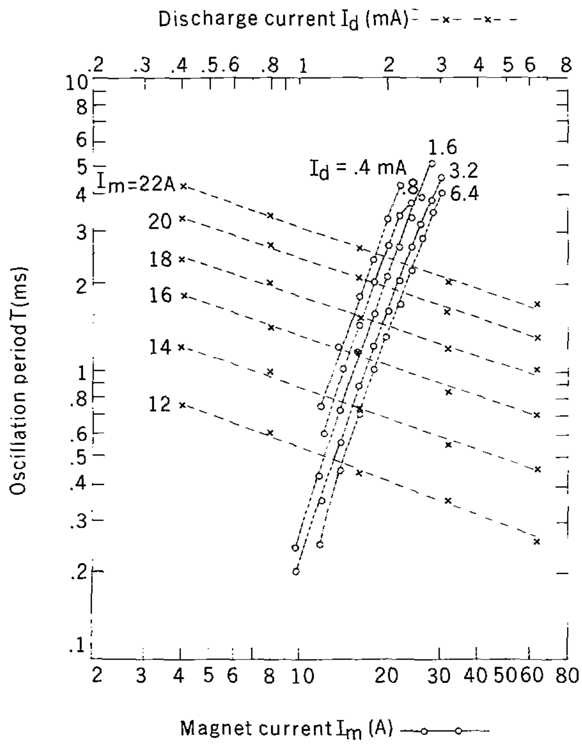


Fig. 4. Oscillation period as function of magnet current (solid lines) and discharge current (dashed lines).

addition an inverse-square variation with collision frequency but no variation with charged-particle density (discharge current).

Numerous experiments with the same sealed discharge tube were carried out over a period of one week. The results were similar, but from day to day there was a slight decrease in the oscillation period (about 10 percent per day). Most probably this was caused by a decrease in ambient gas pressure due to self-pumping of the sealed discharge tube. A less likely influence might have been the gradual buildup of a film of sputtered metal over the inside of the glass near the cathode; such a conducting film could influence the instability by changing the boundary conditions inside the tube.

The two factors of changing gas pressure and buildup of sputtered metal may have contributed as well to an increase with time in occasional "mode jumping" to quite different lines on the graphs of oscillation period against magnet current. The spurious mode lines appear to have slopes of unity but one cannot be completely sure due to a shortage of experimental points. It was found that mode jumping could be largely eliminated by performing the pulsed "ringing" type of experiment of Fig. 3; the curves of Fig. 4 were obtained in this manner.

The oscillations were detected readily by small metal plates (1 cm square and 2 cm square) taped to the side of the discharge tube and connected directly to an oscilloscope. The oscillation amplitude and phase remained essentially unchanged as the pickup plates were moved to various locations around the tube circumference and along its length. The oscillations also were readily detected superposed on the voltage between the discharge electrodes.

IV. Conclusions

Observations have been made on audiofrequency coherent sinusoidal oscillations triggered by a small dc bias on a wire probe in a magnetized dc cold-cathode discharge in neon at 70 μm Hg pressure. When sinusoidal, the oscillation is of the order of 30 mV peak-to-peak and when distorted is of the order of 120 mV peak-to-peak, as measured by a nearby probe immersed in the plasma; the oscillation is therefore very easy to detect. The preceding voltages are of the order of kT/e in typical cool plasmas and so the oscillations could be visible as "ripples" on dc probe characteristics or impedance measurements. In extreme cases the oscillations might modify the average properties of the plasma near the probe.

Oscillation periods have been observed from 0.14 to 14 ms, corresponding to frequencies from 70 to 7000 Hz. The oscillation period is strongly dependent on the magnetic field (cubic variation over a 3:1 field range) and weakly dependent on the discharge current (inverse cube root variation over a 16:1 current range). Pressure dependence is suspected but not proved. There are also indications that other modes can exist. Azimuthal and longitudinal field variations were looked for but not found; evidently the oscillations exhibit little spatial structure and are not confined to the immediate vicinity of the probe.

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