Plasma Density Measurement Using a Frequency Sweeping Short Antenna

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Abstract—**A new scheme has been developed to measure the plasma density directly with the use of a short antenna driven by a sweeping frequency RF source and biased by a variable negative dc voltage.**

I. Introduction

THERE ARE a number of existing diagnostic methods which can be used to measure the plasma density. In most cases, the measurement requires some intermediate steps of calculation. There is still a demand for new methods which can provide a fast and direct reading on the plasma density and also give a reasonable degree of accuracy.

A new method has been developed for this purpose. The probe consists of a short antenna driven by a sweep frequency oscillator and simultaneously biased by a variable negative dc voltage. This method can provide a fast and direct reading on the plasma density and at the same time gives a similar degree of accuracy as the Langmuir probe method. The details of this scheme are given below.

II. Experimental Setup

A typical setup for the present diagnostic scheme is shown in Fig. 1. A short movable monopole (or dipole) antenna or probe is placed in a volume of plasma where the plasma density is to be measured. The probe is driven by a sweep frequency oscillator over a frequency band which covers the local plasma frequency at the probe location. In our experiment, the sweeping frequency band was between 0.4 to 1.4 GHz. To facilitate the measurement, the output of the sweep frequency oscillator may be amplified by an amplifier such as a traveling wave tube amplifier, as used in our experiment. The output of the traveling wave tube amplifier is fed into the probe after passing through a directional coupler and a bias insertion unit. With the help of the directional coupler, the reflected wave from the probe can be channeled to the detector and then to the vertical input of an oscilloscope. The horizontal input of the oscilloscope is fed by the sweeping voltage directly from the sweep frequency oscillator. Thus, the curve displayed on the oscilloscope represents the reflected wave from the probe versus the sweeping frequency. The probe is also biased by a negative dc voltage through the bias insertion unit. When this negative bias voltage is varied, preferably manually, the lower frequency band of the curve displayed

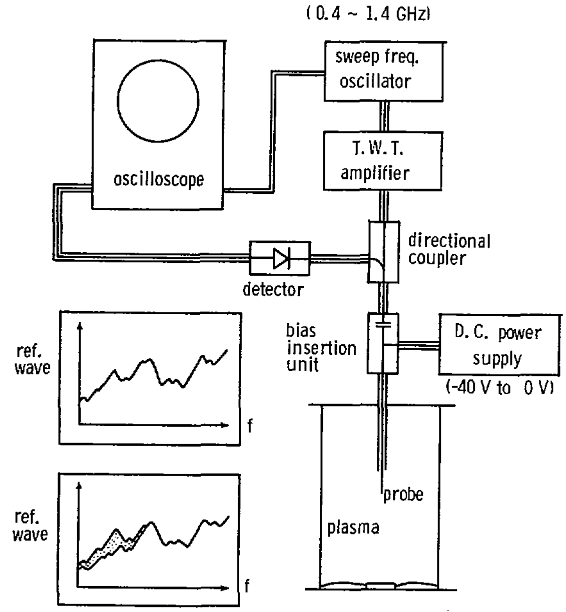

Fig. 1. Schematic diagram of probe and system.

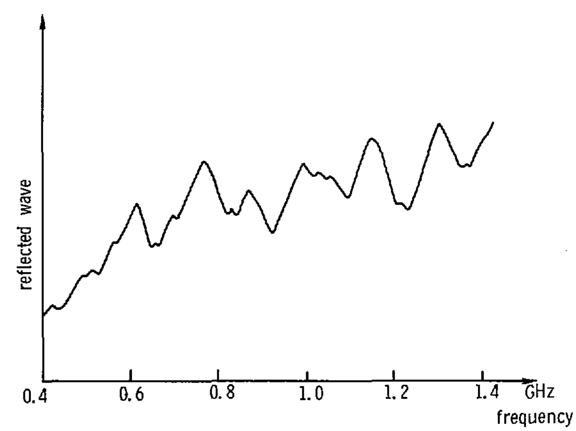

Fig. 2. RW-SF curve (without dc bias).

on the oscilloscope is significantly altered. The upper bound of this altered frequency band gives the direct reading of the local plasma frequency at the probe location.

The typical reflected wave versus sweeping frequency (RW-SF) curve displayed on the oscilloscope before the application of the bias voltage is shown in Fig. 2. The peaks and dips in the curve are probably due to the electromagnetic reflection from the antenna (probe) tip and also due to electroacoustic resonances excited in the plasma sheath surrounding the probe. It is a well-known phenomenon that for a particular profile of plasma sheath, there exist

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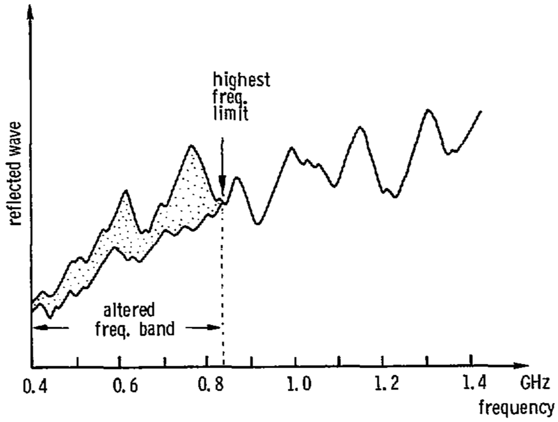


Fig. 3. RW-SF curve (with negative dc bias).

certain discrete frequencies at which electroacoustic resonances, or Tonks–Dattner's resonances, can be excited in the plasma sheath surrounding the probe. When an electroacoustic resonance is excited, more power is transferred from the probe into the plasma sheath to set up this resonance, thus, causing a dip in the RW-SF surve.

When the negative dc bias voltage is slowly varied, the lower frequency portion of the RW-SF curve is significantly altered as indicated in Fig. 3. It was found that the highest frequency limit of this altered frequency band of the RW-SF curve was equal to the local plasma frequency at the probe location. In our experiment, the bias voltage was varied from 0 to -40 volts. It was found that the range of variable bias voltage does not change the altered band of the RW-SF curve, but only affects the amplitude of the alternation of the curve. Thus, with any adequate range of the variable dc bias voltage, one can find a unique value for the highest frequency limit of the altered frequency band of the RW-SF curve, or a unique local plasma frequency at the probe location. This local plasma frequency can be read directly from the oscilloscope without any intermediate calculation.

In our experiment, it was found that when the probe was biased positively with respect to the plasma and varied from 0 to $+25$ volts, the RW-SF curve was not altered at all. When the bias voltage exceeds $+25$ volts, the probe starts to draw a heavy dc current from the plasma causing a red glowing at the antenna tip. It was then concluded that the application of a positive dc bias voltage to the probe had no effect on the RW-SF curve and played no role in the present diagnostic scheme.

III. Experimental Results

In our experiment, a large volume of plasma was produced with a mercury arc discharge in a plasma tube. The plasma tube was an open end pyrex bell jar with the anode placed on the top end and a mercury pool cathode placed at the bottom end of the bell jar. The density of the plasma was easily varied by changing the discharge current or the plasma current of the plasma tube. In the normal operation, the plasma current of the plasma tube could be varied from 5 to 50 amperes to produce a wide range of plasma density.

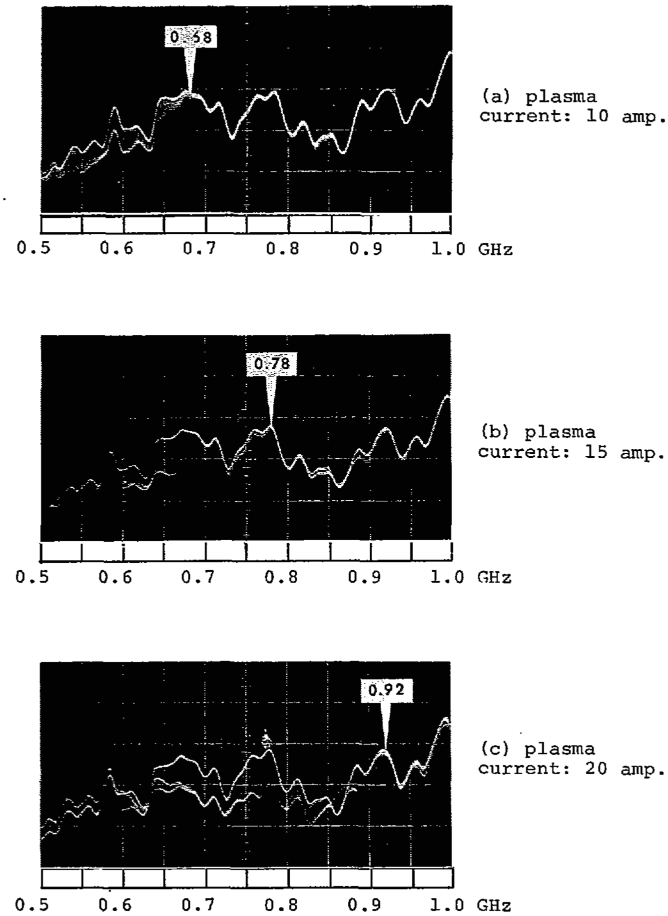


Fig. 4. Oscillograms of reflected wave versus sweeping frequency curves for various plasma currents. Frequency range from 0.5 to 1.0 GHz.

A thin wire monopole of about 5 mm length was placed in the central part of the plasma tube to measure the plasma frequency at the probe location. Fig. 4 shows the experimental results obtained for the cases of three different plasma currents. When the plasma current is 10 amperes and the probe bias voltage is varied from 0 to -40 volts, the RW-SF curve displayed on the oscilloscope is shown in Fig. 4(a). It is clearly seen in this oscillogram that the lower frequency band (0.5 to 0.68 GHz) is substantially altered. The highest frequency limit of the altered frequency band, or the local plasma frequency at the probe location, is 0.68 GHz. When the plasma current is increased to 15 amperes without changing the probe location, the RW-SF curve for this case is shown in Fig. 4(b). The altered frequency band due to the variation of the bias voltage (0 to -40 volts) is from 0.5 to 0.78 GHz, implying that the local plasma frequency at the probe location is increased to 0.78 GHz. When the plasma current is further increased to 20 amperes and not moving the probe, the altered frequency band of the RW-SF curve is from 0.5 to 0.92 GHz as can be seen in Fig. 4(c). This indicates that the local plasma frequency at the probe location is 0.92 GHz.

To check the validity of the assumption that the highest frequency limit of the altered frequency band of the RW-SF curve is the local plasma frequency at the probe location,

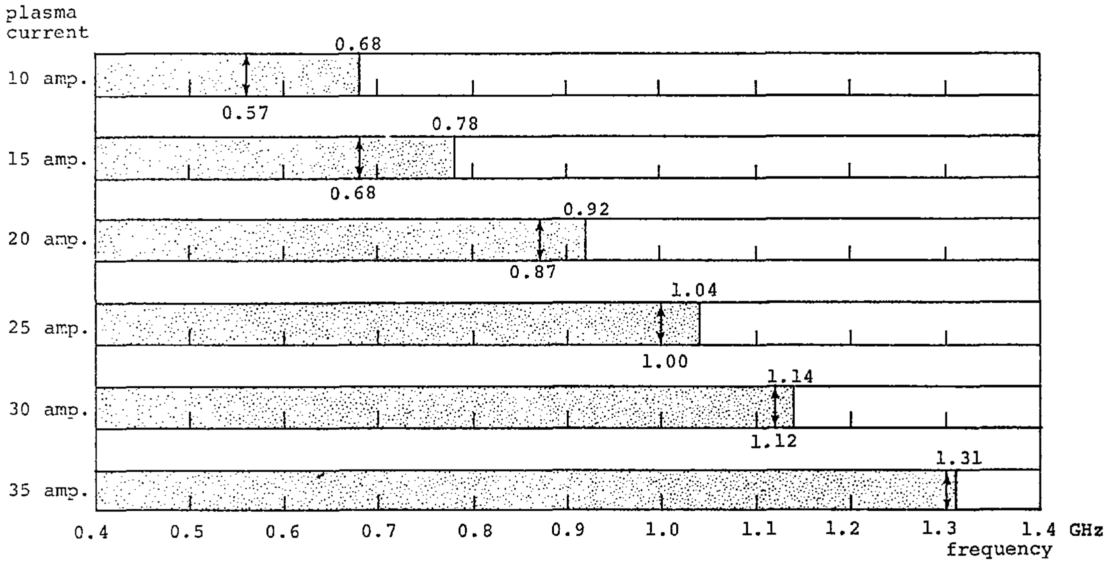


Fig. 5. Affected frequency bands of RW-SF curves for cases of various plasma currents. (shaded is affected frequency band. ↕ is local plasma frequency measured by Langmuir probe method.)

we have measured the plasma densities for different plasma currents at the probe location by using the Langmuir probe method. The results based on the Langmuir probe method are compared with the results obtained by the present method in Fig. 5. Experiments were conducted at six different plasma currents: 10, 15, 20, 25, 30, and 35 amperes. For each case, the altered frequency band of the RW-SF curve, due to the variation of the bias voltage, is indicated by the shaded area. The local plasma frequency at the probe location, as measured by the Langmuir probe method, is indicated by a double-headed arrow. It is seen in Fig. 5 that the highest frequency limit of the altered frequency band of the RW-SF curve is quite close to the local plasma frequency measured by the Langmuir probe method in all six cases. For the lower plasma current (density) cases, the agreement between these two methods is only fair; however, the agreement improves as the plasma density is increased. After numerous experiments, it was concluded that the present method can measure the plasma density with the same degree of accuracy as the Langmuir probe method. The main advantage of the present method is the fast and direct reading of the plasma frequency as compared to the Langmuir probe method which requires intermediate steps of calculation.

IV. Interpretation of Experimental Results

To interpret the experimental results, the physical mechanisms for the electroacoustic resonance proposed by Baldwin [1] and Parbhakar and Gregory [2] will be used. This physical mechanism is the following. When an electromagnetic wave is incident upon a bounded nonuniform plasma, the electromagnetic field will excite an electroacoustic wave at the critical density point on the density profile where the local plasma frequency is equal to the frequency of the incident wave. The electromagnetic energy is coupled to the electroacoustic wave at this critical density point. The excited electroacoustic wave then propagates in both directions; one attenuates into the overdense plasma and the other propagates and sets up a standing wave in the underdense plasma region or the plasma sheath. In this physical mechanism, it is implied that in order to excite an electroacoustic wave, an electromagnetic wave is required to interact with the plasma at the critical density point. If no critical density point exists in the plasma, an electroacoustic wave may not be excited.

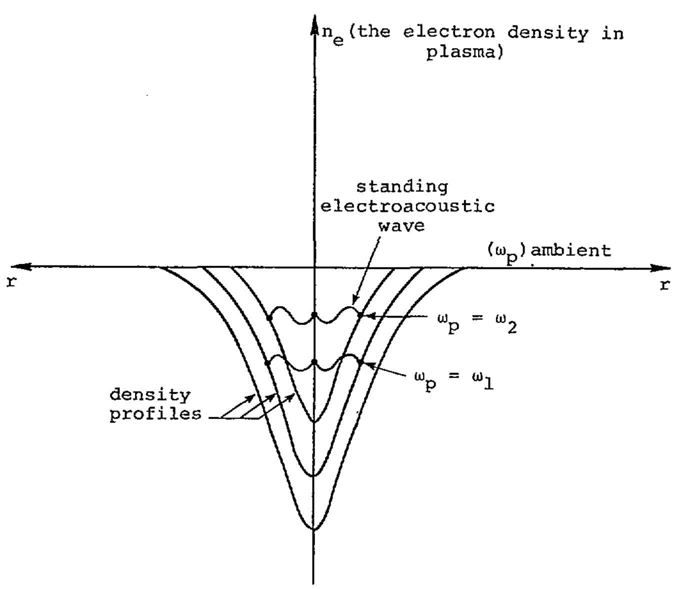


Fig. 6. Plasma density profiles surrounding probe for various negative bias voltages.

In our experiment, when the probe is biased negatively with respect to the plasma, electrons in the probe vicinity are repelled. This creates an electron-deficient region surrounding the probe, or a conventional plasma sheath with a density profile as shown in Fig. 6.

For this situation, the local plasma frequency in the plasma sheath region is lower than the ambient plasma frequency at the probe location. When the probe frequency is lower than the ambient plasma frequency, an electroacoustic wave can be excited at a critical density point on the density profile of the plasma sheath. This excited electroacoustic wave attenuates outwardly, but can propagate inwardly because the plasma sheath region is underdense with respect to this frequency. The inward electroacoustic wave is essentially trapped in the finite plasma sheath region, so that it will set up a standing wave pattern. Furthermore, when the width of the plasma sheath is roughly on the order of an integral multiple of the half electroacoustic wavelength, the electroacoustic wave will reach a resonance condition. Whenever the electroacoustic resonance is reached at a particular probe frequency and at a particular probe bias voltage, more power is transferred from the probe to the plasma resulting in a dip in the reflected wave from the probe. Thus, as the probe bias voltage is varied, while the probe frequency is being swept simultaneously, the electroacoustic resonance is reached at some discrete frequencies. Since these discrete frequencies are dependent on the density profile of the plasma sheath, which is controlled by the probe bias voltage, the lower frequency portion of the RW-SF curve will be altered when the probe bias voltage is varied.

When the probe frequency is higher than the ambient plasma frequency at the probe location, no critical density point can be found at any point in the plasma volume. Thus, no electroacoustic wave can be excited in the plasma. If no electroacoustic wave is excited for a frequency band higher than the ambient plasma frequency, no significant change on the RW-SF curve can be observed when the probe bias voltage is varied.

Therefore, when the negative probe bias voltage is varied, only the part of the RW-SF curve where the probe frequency is lower than the ambient plasma frequency at the probe location is affected. This also means that the highest frequency limit of the altered frequency band of the RW-SF curve is equal to the local, ambient plasma frequency at the probe location.

When the probe is biased positively with respect to the plasma, the electron density in the vicinity of the probe is increased and it may create a density profile surrounding the probe as shown in Fig. 7.

When the probe frequency is continuously swept over a band and, at the same time, the antenna bias voltage is varied, let us consider a particular instance when the probe frequency is ω_1. If ω_1 is higher than the ambient plasma frequency, an electroacoustic wave is excited at the critical density point where $\omega_p = \omega_1$ somewhere on the density profile in the probe vicinity. The excited electroacoustic wave can propagate outwardly in a large volume of underdense ambient plasma in a form of a traveling wave. It appears that the amount of energy used to excite the electroacoustic wave remains rather constant for various probe frequencies and various density profiles which are changed by the variation of probe bias voltage. The excited electroacoustic wave which propagates inwardly toward the probe becomes evanescent because an overdense plasma surrounds

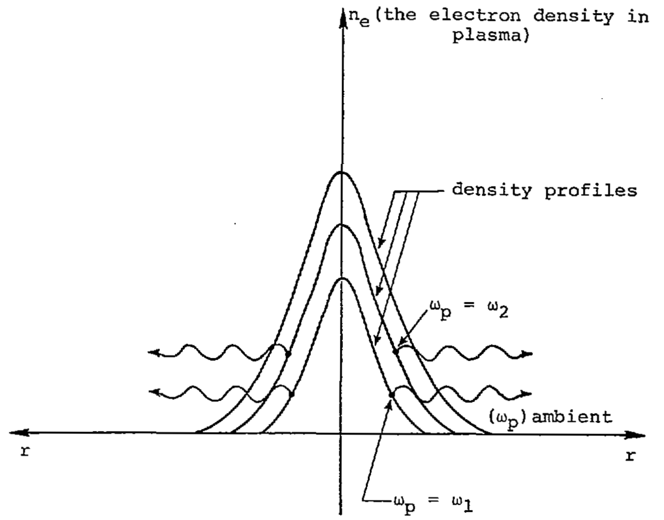


Fig. 7. Plasma density profiles surrounding probe for various bias voltages.

the probe. Thus, no standing electroacoustic wave can be set up in this situation and no electroacoustic resonance can be observed through the reflected wave from the probe.

If the probe frequency is lower than the ambient plasma frequency at the probe location, no electroacoustic wave can be excited or propagated in the plasma because any point in the plasma volume is overdense at this frequency. Therefore, one would not expect to observe any significant change on the RW-SF curve when the probe bias voltage is positive and varied.

The above explanation on the experimental results is completely based on the electroacoustic wave picture. There is another possible explanation for the experimental results based on a simplistic electromagnetic picture. This alternate explanation is as follows. When the probe is biased negatively, the electron-deficient plasma sheath surrounding the probe essentially behaves as a cylindrical capacitor around the probe. The thickness of the capacitor is changed by the variation of the bias voltage. As the probe frequency is being swept for the frequency band lower than the ambient plasma frequency at the probe location, the probe is surrounded by a variable capacitor (varied by the variable bias voltage) and then by a volume of overdense plasma. The evanescent electromagnetic wave from the probe is confined in the vicinity of the probe. Thus, the reflected wave from the probe may be significantly affected by the variation of the capacitor or the variation of the bias voltage. If the probe frequency is higher than the ambient plasma frequency at the probe location, the electromagnetic wave from the probe radiates through the capacitor and then into the underdense plasma. Under this situation, the change in the capacitor may not have a significant effect on the reflected wave from the probe. Thus, the variation of the probe bias voltage has no effect on the higher frequency band of the RW-SF curve which is higher than the ambient plasma frequency at the probe location.

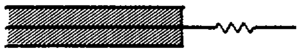
When the probe is biased positively, the electron density in the immediate vicinity of the probe becomes higher than the ambient plasma density and no capacitor is created. The variation of the probe bias voltage simply changes the electron density surrounding the probe and the dc current drawn by the probe. It seems that the variation of the positive dc bias voltage has little effect on the reflected wave from the probe. This may explain why the variable, positive dc bias voltage has no effect on the RW-SF curve.

In addition to the two possible mechanisms described above, a theoretical analysis made by Lin and Mei [3] on the effects of a plasma sheath on the input admittance of a short antenna may provide a theoretical verification for our experimental observation. In their analysis, it was theoretically found that the plasma compressibility has practically no effect on the input admittance of the short antenna at frequencies above the plasma frequency and strong effects at and below the plasma frequency. This result was shown in Figs. 15 and 16 of [3]. This theoretical finding appears to coincide with our experimental observation. However, it is difficult to construct a physical mechanism based on this theoretical result since it was obtained numerically from coupled integral equations.

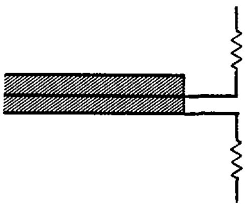
The exact physical mechanism involved in our experimental observation is not well known. It is quite possible that the two mechanisms based on the electroacoustic wave and the electromagnetic wave may all play roles in the experiment since we have positive evidence of the excitation of the electroacoustic wave by the probe and also of the existence of the capacitor (the plasma sheath) surrounding the probe.

V. Improvement

One of the weak points of the present scheme is the irregular shape of the RW-SF curve. If the number of peaks and dips in the RW-SF curve can be minimized, a rather straight RW-SF curve can be obtained. In that case, the alternation on the RW-SF curve due to the variation of the probe bias voltage can be observed more easily. To reduce the peaks and dips in the RW-SF curve, the probe should be matched to some degree so that the reflected wave becomes less frequency dependent. To match the probe, appropriate miniature resistors can be used to load a monopole or a dipole probe as shown in Figs. 8(a) and (b). It is also possible to construct a probe with a terminated coaxial line as shown in Fig. 8(c). The end part of the coaxial line forming the probe is surrounded by a meshed cage structure so that the probe can be in direct contact with the plasma.



(a)



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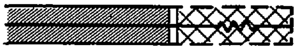

(c)

Fig. 8. Improved loaded probes.

References

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