NOTES

BRIEF contributions in any field of instrumentation or technique within the scope of the Journal should be submitted for this section. Contributions should in general not exceed 500 words.

Digital plasma density determining device*

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A device is described for measuring the time dependent, volume averaged density of a decaying plasma in a large multimode microwave cavity such as is typically used for plasma confinement studies. The technique consists of filling the cavity with microwave radiation and digitally counting the modes observed with a detector as the plasma decays. Since each mode corresponds statistically to a constant density increment, the density at a given time is proportional to the number of modes that appear as the density decays to zero. Experiments in a toroidal octopole show good agreement with density as measured by other methods.

One of the most important properties of a plasma is its density, and for many purposes, such as where the density profile is known by other means, it is adequate to measure the spatially averaged density. For low density plasmas ($n \lesssim 10^{13}$ cm^{-3}), a convenient nonperturbing technique involves the use of microwaves whose phase velocity is altered by the permittivity of the medium through which they propagate. For an unmagnetized collisionless plasma, the permittivity is

$$\epsilon=\epsilon_0-ne^2/m\omega^2, \tag{1}$$

where ϵ_0 is the permittivity of free space and ω is the microwave frequency.

Examples of such microwave techniques are the fundamental mode method[1] and the microwave interferometer.[2] The first method requires a particular cavity shape and microwave frequency as well as a knowledge of the density profile. The second method measures a line averaged density but requires good frequency stability and good collimation of the microwave beam to avoid excitation of cavity resonances.

The method described here is patterned after a technique used by Fessenden and Smullin[3] in which a high order mode cavity of arbitrary shape is filled with microwave radiation and the average density is determined by counting the modes which are excited as the density decays monotonically to zero. The microwave system is especially simple since all that is required is a low power signal source feeding an antenna, and a diode detector connected to another antenna, at any convenient places in the cavity. The new feature reported here is a circuit that counts the cavity modes and displays the result digitally and as an analog signal proportional to the average plasma density.

When a plasma is introduced into the cavity, a number of modes will shift past the detector, and each mode will correspond to a change in density δn given by

$$\delta n=2\epsilon_0 m\omega\delta\omega/e^2. \tag{2}$$

The average mode spacing $\delta\omega$ is determined by sweeping the frequency of the source in the absence of plasma. If the number of modes is large, the statistical variation of the mode spacing will be unimportant and the density can be determined by counting the modes as the plasma builds up or decays. Since the density must be large enough to shift through many modes but small enough for perturbation theory to be valid, the technique works best for densities in the range

$$1/Q \ll \omega_p^2/\omega^2 \ll 1, \tag{3}$$

where ω_p is the plasma frequency,

$$\omega_p^2=ne^2/\epsilon_0 m.$$

Since the modes generally overlap because of their finite Q, it is important to define quantitatively what is meant by an observable mode. Actually any definition will suffice as long as it is used consistently. Here we assume that a mode exists if the detector response passes through a local maximum as a function of frequency during the calibration or as a function of time during the plasma decay.

Because the modes overlap, a simple discriminator technique is inadequate to detect them reliably. Another approach would be to differentiate the signal and count the zero crossings; however, the low detector signal level (around 2 mV) and the wide variation in pulse widths (from about 1 msec to less than 1 μsec), combined with the noisy electrical environment, make the differentiator approach impractical: it is too sensitive to high frequency noise.

The method used to detect the modes shown in Fig. 1 combines analog and digital circuitry in a way that overcomes the limitations of the above techniques. The detector signal is amplified and applied to an analog-to-digital (A/D) converter. The A/D converter used is a seven bit successive-approximation type of conventional design.[4] Since it is a successive-approximation converter, a sample/hold circuit must be used ahead of it to "freeze" the analog signal while the conversion is taking place. Using a sample/hold constructed

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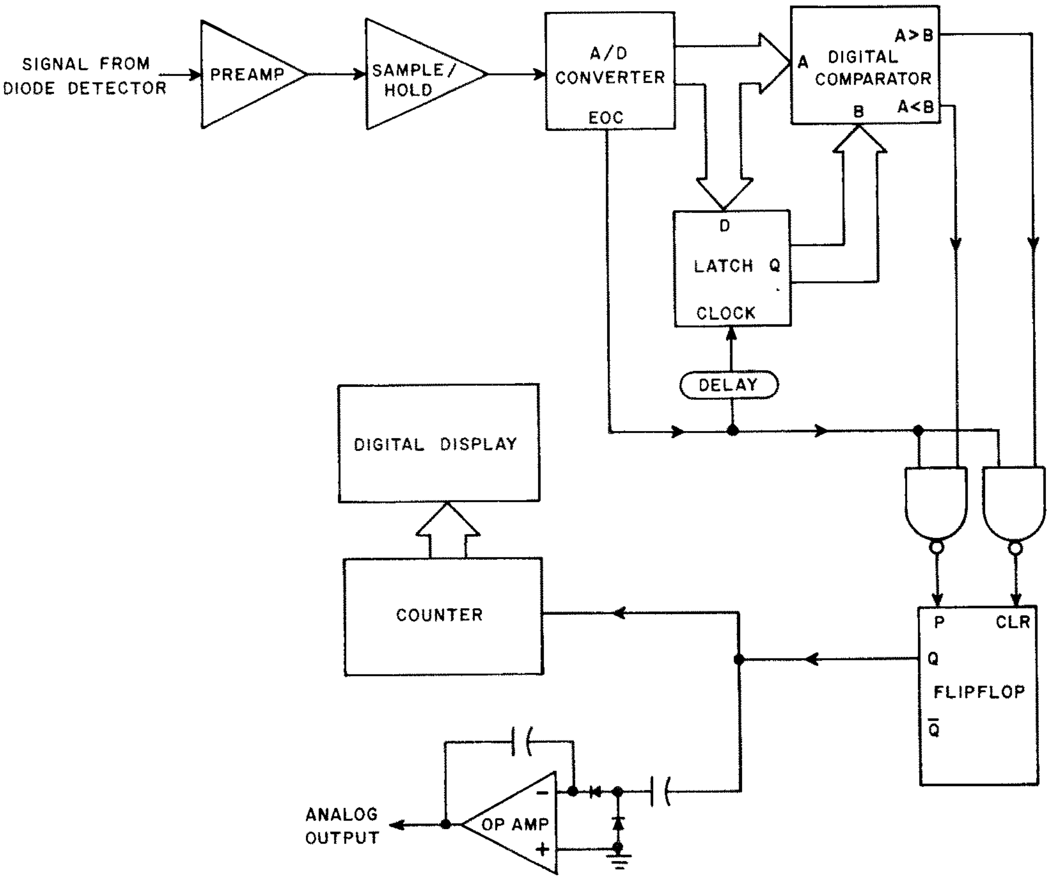

FIG. 1. Block diagram of mode counter circuit. Arrows indicate signal flow.

with discrete components, we were able to achieve a conversion time for the sample/hold A/D combination of about 350 nsec. Since it takes at least three points to unambiguously detect a peak, this means the narrowest pulse widths we could detect were about 1 μsec; there is no maximum limit on the detectable pulse width.

A digital comparator is used to compare each new word from the A/D with the previous word, which is stored in a latch. The end-of-conversion signal from the A/D gates the result of the digital comparison to a flipflop, and after a short delay the comparator signal is disabled and the new word is stored in the latch. If the new word is greated than the old word, the flipflop is cleared and its Q output goes low; if the new word is less than the old word, the flipflop is preset and the Q output goes high. Thus every low-to-high transition on the Q output of the flipflop indicates the presence of a peak. These transitions are counted in a digital counter and the total number of peaks is presented on a digital display.

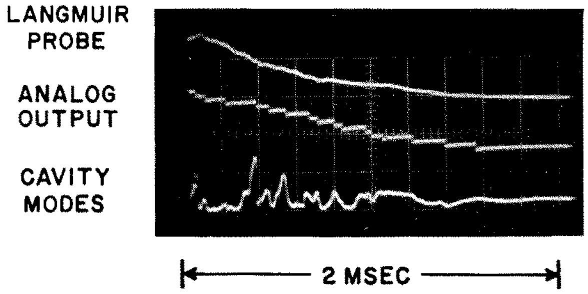

FIG. 2. Typical experiment result showing a plasma density decay as measured by a Langmuir probe and by the mode counter.

The transitions are also used to drive an op-amp charge pump circuit whose output voltage is then proportional to the total number of peaks. This signal is used as the analog output.

The circuit was tested using gun-injected and afterglow microwave plasmas in the Wisconsin supported toroidal octopole.[5] The octopole consists of a low aspect ratio toro dal vacuum cavity with aluminum walls and a volume of 3×10^5

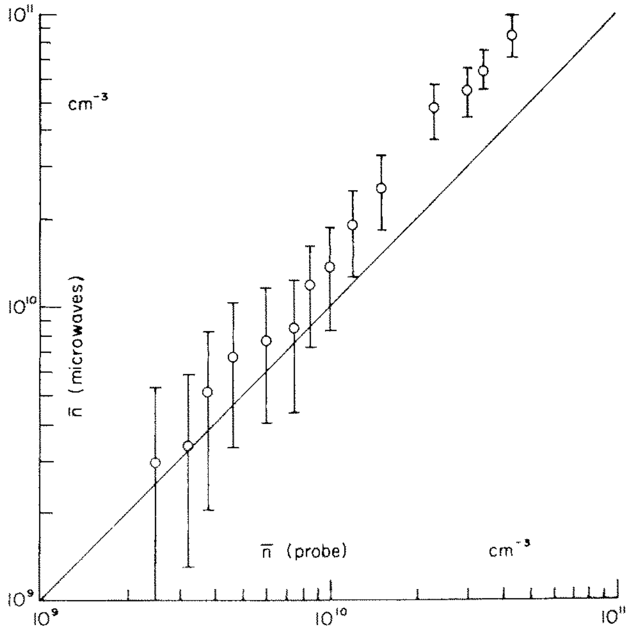

FIG. 3. Comparison of density measured by counting modes with density determined from a Languir probe.

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cm^3. The magnetic field varies from zero to about 7 kG over the volume. The microwave source is a 10 mW, 24 GHz klystron coupled through a waveguide to a hole in the cavity wall. The detector is a 1N26 microwave diode in a waveguide coupled through a hole on the opposite side of the toroidal cavity.

The system was calibrated by sweeping the klystron frequency through about 50 MHz and measuring the average mode spacing. The result is about 3.0 MHz/mode which is consistent with the observed Q of about 10^4, but much larger than the theoretical value of 0.012 MHz/mode, indicating that only a small fraction of the modes are observable. The observable mode spacing corresponds to a density increment of 1.8×10^9 cm^{-3}/mode, which we take as the calibration constant for the system.

A plasma was produced by electron cyclotron resonance heating using a high power pulsed magnetron.[6] The decay of the afterglow plasma density was measured using the mode counting technique and a Langmuir probe. Figure 2 shows typical results. The upper trace is the ion saturation current to a long Langmuir probe that line averages the signal across the plasma midplane. This signal, when corrected for the temperature decay, is approximately proportional to the average density. The middle trace shows the analog output of the mode counting circuit which should be proportional to the average density. The scale is about 2×10^{10} cm^{-3} per large division. The lower trace is the output of the microwave diode showing the succession of about a dozen cavity modes excited as the density decays.

In order to test quantitatively the accuracy of the mode counter, the density was varied by varying the power level of the electron cyclotron resonance heating source. The density was measured using a Langmuir probe, properly corrected for changes in temperature, and using the mode counting technique. The result shown in Fig. 3 indicates agreement within about a factor of two from 3×10^9 cm^{-3} to almost 10^{11} cm^{-3}.

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[2] M. A. Heald and C. B. Wharton, *Plasma Diagnostics with Microwaves* (Wiley, New York, 1965).

[3] T. J. Fessenden and L. D. Smullin in the *Proceedings of the Seventh International Conference on Phenomena in Ionized Gasses* (Beograd, 1966), Vol. III, p. 83.

[4] The successive-approximation converter is similar to that described in *Analog–Digital Conversion Handbook* (Analog Devices, Norwood, Mass., 1972), p. II-82.

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An improved laser-schlieren system for the measurement of shock-wave velocity

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An improved laser-schlieren system for the measurement of shock-wave velocities has been developed which employs a single detector. Calibration of multiple detectors has been obviated. The system has been shown to yield, in addition to the shock-wave velocity, additional information on the arrival time of the contact surface. Shock-tube performance is compared to the predictions of Mirels' theories.

In studies involving the chemical shock tube, the velocity of the incident shock wave is an important parameter since it can be related to the temperature of the shocked gas. In addition, it can be easily measured. The usual method of measuring shock velocity is to time the passage of the shock front past fixed sensors. These sensors must have a response time of less than a microsecond, they must give good space resolution, and they can not interfere with flow in the shock tube. Methods of shock front detection currently used include metal film resistance probes,[1,2] and the Fraunhofer diffraction[3] or Schlieren refraction[4] of a laser beam. This note describes an improvement of the laser-schlieren method.

A laser-schlieren system takes advantage of the change in optical density across a shock front to vary the amount of light falling on a photodetector. Kieffer and Lutz developed this method to study vibrational relaxation in hydrogen[5] and deuterium[6] and it was adapted by Jacobs[7] and D'Amato[8] for velocity measurements. Their system uses a single laser light source split into beams which are transmitted across the shock tube normal to the direction of flow. Each beam has a separate detector. Although there is no theoretical limit to the number of detection stations, the 50% decrease in light intensity at each beam splitting limits the number to three. There is also the difficulty of calibrating each of the multiple detectors to correct for their individual characteristics. This note describes a modification which allows any number of passes with a single light source and a single detector, thus removing this calibration problem.

A series of front-surfaced mirrors (see Fig. 1) reflects the laser beam n times through the shock tube normal to

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