Wide Band Electrostatic Probes for Use in Tenuous Plasmas*

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A derivation is given for the resistance of the sheath surrounding a floating probe and the corresponding limitation to the frequency response. The bandwidth is increased by using probes with built-in attenuators which measure fluctuations in floating potential, electric field, and ion saturation current at frequencies up to 40 MHz with plasma densities as low as 10^9 cm^{-3}.

INTRODUCTION

THE incremental resistance of the plasma sheath which surrounds a floating electrostatic probe can be calculated by expanding the expression for the probe current in a Taylor series about its value at $V=V_f$, where V_f is the floating potential of the probe. At the floating potential, the probe is generally negative with respect to the plasma potential V_p and collects only those electrons whose energy is sufficient to overcome the potential barrier. The flux of ions to the probe is not significantly increased because the electric field exists entirely within the sheath and only affects those ions which are already destined to reach the probe. If we assume a Maxwell-Boltzmann velocity distribution, it can be shown[1] that the current density to a probe near the floating potential is given by

$$j=ne\left(\frac{kT^*}{2\pi m_i}\right)^{\frac{1}{2}}-ne\left(\frac{kT_e}{2\pi m_e}\right)^{\frac{1}{2}}\exp[-e(V_p-V)/kT_e],$$

where m_e and m_i are the electron and ion masses, respectively, and n is the density of either species. $T^*\approx T_i$ the ion temperature whenever $T_i>T_e$. For $T_i<T_e$, the electric fields which reach past the sheath are so large that ions are collected with greater efficiency,[2] and $T^*\approx T_e$ the electron temperature. At the floating potential ($V=V_f$) the current density must, by definition, vanish, or

$$(T_e/m_e)^{\frac{1}{2}}\exp[-e(V_p-V_f)/kT_e]=(T^*/m_i)^{\frac{1}{2}}.$$

This equation defines V_f in terms of the plasma parameters. Expanding $j(V)$ about the point $V=V_f$, retaining only the first order term, gives

$$j=(V-V_f)\left.\frac{dj}{dV}\right|_{V_f}=-(V-V_f)\frac{ne^2}{kT_e}\left(\frac{kT^*}{2\pi m_i}\right)^{\frac{1}{2}}.$$

The sheath resistance is $R_s=-(V-V_f)/jA$, where A is the area of the probe exposed to the plasma. Substitution for j gives

$$R_s=(kT_e/ne^2A)(2\pi m_i/kT^*)^{\frac{1}{2}}.$$

As a numerical example, consider a hydrogen plasma with $kT_i\approx 100$ eV, $kT_e\approx 10$ eV, $n\approx 10^9$ cm^{-3}, and let $A\approx 0.2$ cm^2. We obtain $R_s\approx 10^5\,\Omega$. If the probe has an input capacitance C the time required for the probe potential to readjust to a different plasma potential is given by $\tau=R_sC$. If $C\approx 100$ pF in the previous example, we get $\tau\approx 10$ μsec, corresponding to a cutoff frequency of ≈ 20 kHz. These results have been experimentally verified in plasma studies involving the Wisconsin Toroidal Octupole, for which the above numerical data apply.[3] It has been necessary in this work to use probes with impedance greater than $10^5\,\Omega$ in order to observe the high frequency fluctuations which occur during the injection process.

This paper describes the method used for reducing the probe capacitance to about 0.2 pF, thereby greatly increasing the cutoff frequency. The method has been successfully applied to high impedance double probes for simultaneously measuring floating potential and local electric field, and to low impedance floating double probes where the tips are biased with respect to one another for measuring a rapidly varying plasma density.

HIGH IMPEDANCE PROBES

The frequency response of the probes can be improved by reducing the sheath resistance or by lowering the probe capacitance. The sheath resistance has been successfully reduced by increasing the exposed area of the probe in accordance with the above theory. In cases where the

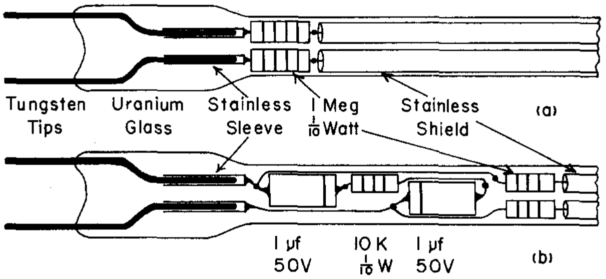

FIG. 1. Construction of attenuated probes. The input capacitance is greatly reduced by installing a 1 MΩ resistor near the tips. (a) High impedance probe for measuring electric fields and floating potentials. (b) Low impedance probe for measuring ion saturation current.

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[1] F. F. Chen in *Plasma Diagnostic Techniques*, R. H. Huddlestone and S. L. Leonard, Eds. (Academic Press Inc., New York, 1965), Chap. 3.

[2] D. Bohm, E. H. S. Burhop, and H. S. W. Massey in *Characteristics of Electrical Discharges in Magnetic Fields*, A. Guthrie and R. K. Wakerling, Eds. (McGraw-Hill Book Company, Inc., New York, 1949), Chap. 2.

[3] D. W. Kerst, R. A. Dory, W. E. Wilson, D. M. Meade, and C. W. Erickson, Phys. Rev. Letters **15**, 396 (1965).

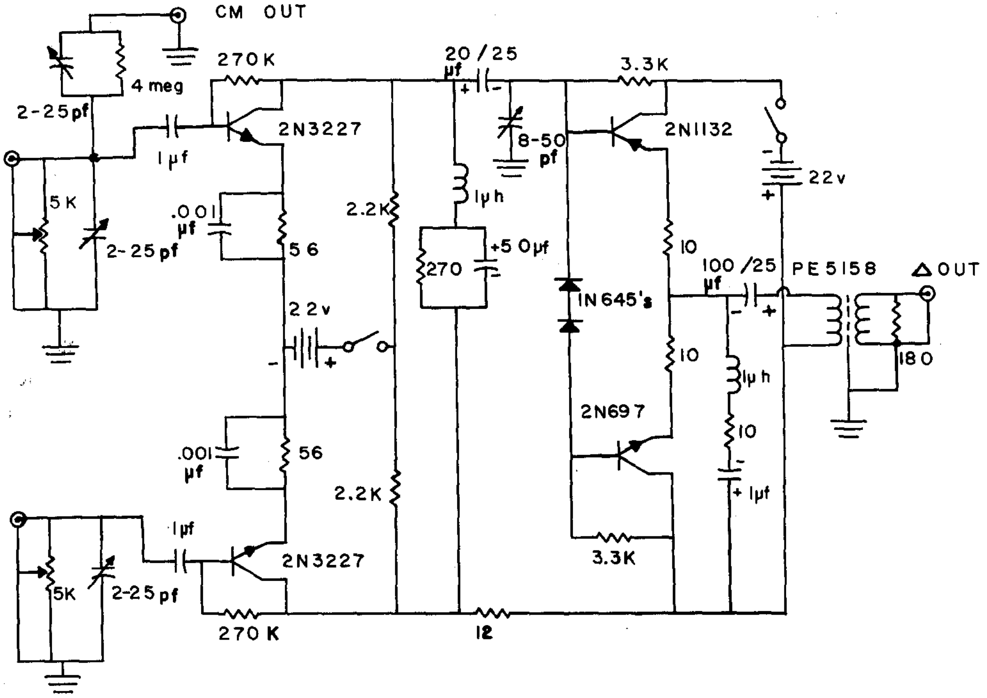

FIG. 2. Wideband differential amplifier for use with attenuated probes. Common mode rejection is achieved by floating the amplifier and taking the output across the secondary of a pulse transformer. Wide bandwidth is obtained by using the pair of RLC networks.

probe capacitance is primarily due to the shielded lead to the probe, a cathode follower can be used to drive the shields. Care must be taken to insure that the impedance between the shield and ground is sufficiently low to prevent the plasma from capacitively driving the shield.

An alternate method is to install a resistor near the probe tip to serve as part of an RC compensated attenuator. Figure 1(a) shows the construction of an attenuated double probe. The resistors are 1 MΩ, $\frac{1}{10}$ W carbon (Allen-Bradley, type TR) and are found experimentally to have an equivalent parallel capacitance of about 0.2 pF, or an RC product of 0.2 µsec. Unfortunately, the capacitance is not evenly distributed along the resistor, so a perfect balance is not easily achieved. If the probe is used to drive 100 pF of cable capacitance, the cable should be terminated with about 2000 Ω, giving an attenuation factor of 500.

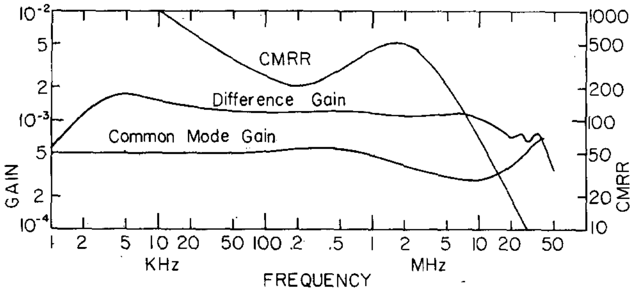

FIG. 3. Typical frequency response of attenuated probe with differential amplifier. The common mode signal is proportional to floating potential, the difference signal is proportional to electric field, and the common mode rejection ratio (CMRR) is the ratio $V_f/\Delta V$ for which the difference signal and the error signal are equal.

In constructing the probes, 0.75 mm diam tungsten tips are sealed into uranium glass so that they are 7 mm apart and protrude 7 mm beyond the glass. It should be recalled that the theory of double probes is valid only when the separation between the tips is much greater than a Debye length.[4] The uranium glass is sealed to one end of a 6 mm o.d. glass tube. The tips can be cleaned by dipping them into a saturated solution of sodium nitrite and passing an alternating current of about 1 A between them for a few seconds. Leads are brought to the tips through two 1.5 mm diam stainless steel tubes which serve to shield the leads from the plasma. Each lead is connected to a resistor which is in turn attached to a stainless steel sleeve, allowing it to be slipped over the tungsten electrodes in the final step of the assembly, making a snug fit.

Figure 2 shows one differential amplifier which has been used with the high impedance probes. By letting the entire amplifier float at the common mode potential [$(1/500)V_f$] and taking the output across a pulse transformer (Pulse Engineering, PE-5158), small difference signals can be measured in the presence of common mode signals which may be much larger. The common mode is read on one of the inputs through a second attenuator capable of driving a 3 m length of RG-114A/U cable connected to the 1 MΩ input of an oscilloscope.

Figure 3 shows the over-all gain of the probe and amplifier and the common mode rejection ratio as a function of frequency. The gain at low frequencies is limited by the finite magnetizing inductance of the pulse transformer. The

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[4] M. Sugawara and Y. Hatta, J. Appl. Phys. 36, 2361 (1965).

high frequency cutoff is caused by leakage inductance in the pulse transformer and frequency limitations in the amplifier. The bandwidth is increased by the RLC networks shown in Fig. 2 which reduce the gain over the midrange of frequencies. The common mode rejection ratio is limited by asymmetries in the probe and amplifier input circuit, and by the interwinding capacitance in the pulse transformer. The circuit is balanced by applying a rectangular repetitive pulse to both probe tips simultaneously while adjusting the input potentiometers and trimmers for minimum difference output. It is also quite important to adjust the positions of the resistors in the probe relative to one another, until the difference output is smallest.

Several words of caution are in order. The resistors in the probe cannot be shielded since this would shunt out their parallel capacitance, severely limiting the frequency response. Plasma signals may couple capacitively through the glass to the resistor giving an output which is larger and shifted in phase from the real signal. This effect is not too troublesome if the resistors are placed near the tip of the probe and if the shield is extended close to the body of the resistor. When transient magnetic fields are present, care must be taken to avoid ground loops. Furthermore, any inductance in the ground lead to the amplifier forms a series resonant circuit with the plasma to shield capacitance producing resonances in the probe response characteristics. In operation, the common mode and difference outputs are fed into separate channels of a dual beam oscilloscope, where floating potential and local electric field are simultaneously displayed as a function of time.

LOW IMPEDANCE PROBES

With a slight modification [Fig. 1(b)], the high impedance floating probe can be used to measure density and electron temperature[5] in the presence of rapidly fluctuating plasma potentials. If the plasma potential changes faster than the response time of the probe, both tips may be driven to saturation and the current flow between the tips is zero. Figure 4(a) shows the circuit at the probe tip and Fig. 4(b) shows the modification which must be made to the input circuit of the differential amplifier. The capacitors in the end of the probe are 1 μF, 35 V tantalum electrolytics (Sprague 150D, 3.43 mm diameter). The capacitors are charged by the 22 V bias batteries in the amplifier through the 1 MΩ resistors which also serve as the top half of a compensated attenuator. The signal read between the tips is proportional to the current through the 10 kΩ resistor. Such an arrangement is suitable only for pulsed plasmas where the capacitor voltage does not decay appreciably during the time that the plasma is present. Electric fields, which may be present, should be shorted out by the 10 kΩ resistor.

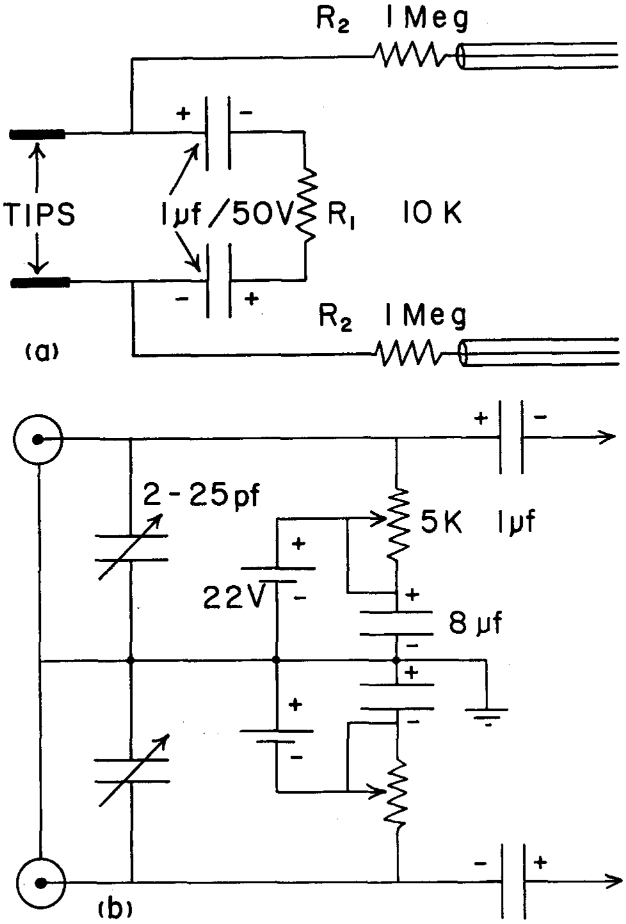

FIG. 4. (a) Circuit used in low impedance probes. The capacitors are kept charged by the 1 MΩ resistors which also serve as part of a compensated attenuator. (b) Modification required for the input circuit of the amplifier shown in Fig. 2, when used with low impedance probes.

It should be noted that since neither tip is actually at the floating potential, the expression for the sheath resistance is not strictly valid. The resistance to the negative tip is higher than predicted and the resistance to the positive tip is lower, but the parallel combination is approximately constant. In situations where the density is high for a considerable time and then drops rapidly to some small value, measurements of the low level signal are especially difficult because of pulse transformer overshoot caused by the finite magnetizing inductance. The only solution is to use a large inductance transformer, such as a PE-5163, and a low value load resistor.

The values of the components in the probe must be carefully chosen. In Fig. 4(a), R_1 should be large to maximize the signal output, but not so large that the maximum voltage drop across it is an appreciable fraction of the capacitor bias voltage. Two capacitors are used in series to increase the voltage rating. If more gain is required, the value of R_2 can be lowered at the expense of frequency re-

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[5] E. O. Johnson and L. Malter, Phys. Rev. **80**, 58 (1950).

sponse. For example, with $R_2 = 100$ kΩ, the gain is increased by a factor of 10, but the response is limited to about 2 MHz. The balancing procedure is identical to that for high impedance probes, except that the bias voltage must be reduced to zero. This is necessary because the resistance of the 1 MΩ resistors is slightly voltage dependent. Since many of the problems which remain are related to the pulse transformer, it is often desirable to use a differential amplifier which does not employ a pulse transformer. In fact, the Tektronix type G differential preamplifier has been used for many of the functions described in this paper.

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Dual Beam Stopped Flow Spectrophotometer Utilizing Modulated Xenon Arcs*

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This paper describes a dual beam stopped flow apparatus for quantitatively observing rapid (up to 250 sec^{-1}) chemical reactions in turbid suspensions. The unit employs two commercial 150 W xenon arc light sources modulated to produce square light pulses at 5000 cps; two wavelengths of light are selected by monochromators, and the light is delivered to the reaction cuvette of a conventional stopped flow apparatus via a fiber optic light guide "Y." Current and light intensity feedback are utilized to control lamp intensity; simple transistor choppers demodulate the measuring photomultiplier output, and a second photomultiplier is utilized in a differencing scheme to reduce effects of residual lamp instability. The instrument has a limit of detectability of 1×10^{-3} optical density units; crosstalk of signal from one channel into the other channel is 6% of the change being measured. An example of instrument performance is presented; as now constructed, the instrument provides time resolution at least 5 times higher and reagent economy more than 20 times higher than other available dual wavelength spectrophotometers.

1. INTRODUCTION

In 1951 Chance[1] described a dual wavelength spectrophotometer used for kinetic studies in scattering suspensions. His basic design has been used in several other instruments and is presently available in a commercial unit.[2] In that design, a source of light illuminates two monochromators from which two wavelengths of light are selected; these two wavelengths are alternately passed through the sample to be studied by switching them with a vibrating mirror. The light passed by the suspension is detected with a photomultiplier and the photomultiplier output is subsequently synchronously and phase sensitively demodulated, amplified, and used to drive a recorder. The readout is essentially the difference between the absorbance at the two wavelengths utilized; in this way, apparent changes in absorbancy due to nonspecific light scattering are cancelled out in first order.

A basic limitation of these instruments is that the 60 cps rate used to switch between wavelengths precludes continuous measurements of changes in absorbancy more rapid than about 5 sec^{-1}. In principle this limitation can be overcome simply by increasing the rate of switching between the two wavelengths of light. This might be accomplished, for example, as in a recently described split beam spectrophotometer which switches between reference and sample cuvette at a rate of 12 kc with a rapidly oscillating mirror[3]; alternatively, one might use rapidly rotating perforated disks to obtain the required high switching rate. However, in view of the severe mechanical problems involved in constructing such systems, we have used instead two xenon arcs modulated to yield square light pulses 180° out of phase at 5 kc. This scheme, of course, precludes mechanical problems and permits observation of absorbancy changes of up to 250 sec^{-1}. To provide flow and mixing characteristics commensurate with this measuring speed, the reaction chamber has been reduced in volume to 60 mm^3 using the stopped flow apparatus of Gibson and Milnes[4]; measurement can be made on a sample as small

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[1] B. Chance, Rev. Sci. Instr. **22**, 634 (1951).

[2] American Instrument Company, Silver Springs, Maryland.

[3] W. Niesel, D. W. Lubbers, D. Schneewolf, J. Richter, and W. Botticher, Rev. Sci. Instr. **35**, 578 (1964).

[4] Q. H. Gibson and L. Milnes, Biochem. J. **91**, 161 (1964).