Lecture Notes on

**Langmuir Probe Diagnostics**

**INTRODUCTION**

Of all the ways to measure a plasma, the Langmuir probe is probably the simplest, since it consists of sticking a wire into the plasma and measuring the current to it at various applied voltages. However, it is an intrusive, not remote, technique; and the .wire. must be carefully designed so as not to interfere with the plasma nor be destroyed by it. Worse than that, the interpretation of the current-voltage (*I . V*) curves is difficult and has spawned a large literature of theoretical papers. In a short lecture, little of this can be discussed in detail. Specialized topics and related electrostatic diagnostics, such as emissive probes, double probes, capacitive probes, oscillation probes, probes in flowing or high pressure plasmas, and probes in a magnetic field can be mentioned only summarily. On the other hand, the most widespread use of Langmuir probes at present is in the semiconductor industry, where radiofrequency(rf) sources are used to produce plasmas for etching and deposition. These partially ionized plasmas require special techniques in probe construction and theory. Emphasis will be given to this new forefront of diagnostics research.

**II. DESIGN OF PROBES AND CIRCUITS FOR RF ENVIRONMENTS**

**A. Probe construction**

Since the probe is immersed in a harsh environment, special techniques are used to protect it from the plasma and vice versa, and to ensure that the circuitry gives the correct *I .* *V* values. The probe tip is made of a high-temperature material, usually a tungsten rod or wire 0.1−1 mm in diameter. The rod is threaded into a thin ceramic tube, usually alumina, to insulate it from the plasma except for a short length of exposed tip, about 2−10 mm long. These materials can be exposed to low-temperature laboratory plasmas without melting or excessive sputtering. To avoid disturbing the plasma, the ceramic tube should be as thin as possible, preferably < 1 mm in diameter but usually several times this. The probe tip should be centered in the tube and extend out of its end without touching it, so that it would not be in electrical contact with any conducting coating that may deposit onto the insulator. The assembly is encased in a vacuum jacket, which could be a stainless steel or glass tube 1/4″ in outside diameter (od). It is preferable to make the vacuum seal at the outside end of the probe assembly rather than at the end immersed in the plasma, which can cause a leak. Ideally, only the ceramic part of the housing should be allowed to enter the plasma. Some commercial Langmuir probes use a rather thick metal tube to support the probe tip assembly, and this can modify the plasma characteristics unless the density is very low. In dense plasmas the probe cannot withstand the heat unless the plasma is pulsed or the probe is mechanically moved in and out of the plasma in less than a second. When collecting ion current, the probe can be eroded by sputtering, thus changing its collection area. This can be minimized by using carbon as the tip material. Ordinary pencil lead, 0.3mm in diameter works well and can be supported by a hypodermic needle inside the ceramic shield. One implementation of a probe tip assembly is shown in Fig. 8. An example of a right-angled.

probe with rf compensation circuitry is shown in Fig. 9. Commercial probes are available from Hiden Analytical and Scientific Systems, among others. The probe tip assembly of the Hiden system is shown in Fig. 10. This has replaceable probe tips, well centered, and an extremely large auxiliary electrode (described later)

A flat probe would seem to the simpler, since it would just draw the Bohm current and the sheath area would not change with probe bias. However, the current has to come from somewhere. In order for the probe not to disturb the plasma, the surface from which the current comes must be much larger than the probe surface. In that case, the probe acts like a spherical probe, and the current will not saturate. The disturbance is minimized if the flat probe is part of a wall, but changing the probe bias would still affect the collection area. The planarity of the collecting surface can be improved by adding a guard ring, co-planar with the probe and biased to the same Vp. The current to the guard ring is affected by edge effects, but it is not measured. Only the current to the central probe area with a planar sheath is measured.



Fig. 8. A carbon probe tip assembly with rf compensation circuitry



Fig. 9. A right-angled probe with rf compensation for 27MHz

**B. Probe circuits**

There are two basic ways to apply a voltage *V* to the probe and measure the current *I* that it draws from the plasma, and each has its disadvantages. In Fig. 12a, the probe lead,taken through a vacuum fitting, is connected to a battery or a variable voltage source (*bias supply*) and then to a termination resistor *R* to ground. To measure the probe current, the11voltage across *R* is recorded or displayed on an oscilloscope. This arrangement has the advantagethat the measuring resistor is grounded and therefore not subject to spurious pickup.Since the resistor is usually 10-1000Ω, typically 50Ω, this is not a serious problem anyway.The disadvantage is that the bias supply is floating. If this is a small battery, it cannot easilybe varied. If it is a large electronic supply, the capacitance to ground will be so large that acsignals will be short-circuited to ground, and the probe cannot be expected to have good frequencyresponse. The bias supply can also act as an antenna to pick up spurious signals. Toavoid this, one can ground the bias supply and put the measuring resistor on the hot side, as shown in Fig. 12b. This is usually done if the bias supply generates a sweep voltage. However, the voltage across *R* now has to be measured with a differential amplifier or some other floating device; or, it can be optoelectronically transmitted to a grounded circuit. Commercial hardware can use a floating analog-to-digital converter to record the voltage across *R*. The probe voltage *V*p should be measured on the ground side of *R* so as not to load the probe with another stray capacitance.

To measure plasma potential with a Langmuir probe, one can terminate the probe in a high impedance, such as the 1 MΩ input resistance of the oscilloscope. This is called a *floating probe*. A lower *R*, like 100K, can be used to suppress pickup. The minimum value of *R* has to be high enough that the *IR* drop through it does change the measured voltage. A rough rule of thumb is that *Is*at*R* should be much greater than *T*eV, or *R* >> *T*eV/*I*sat, where *I*sat is the ion saturation current defined above. The voltage measured is not the plasma potential but the floating potential. The large value of *R* means that good frequency response is difficult to achieve because of the *RC* time constant of stray capacitances. One can improve the frequency response with *capacitance neutralization* techniques, but even then it is hard to make a floating probe respond to rf frequencies. The rule of thumb quoted above comes from the circuit diagram of Fig. 13, where the load line of the terminating resistor is shown together with the probe characteristic. The line on the left is for a small resistor used to measure current; its slope is nearly vertical, so that the marked intersection with the *I . V* curve gives the current near the set point *V*p. Note that *I*e = −*I* is plotted vertically, so that theload lines have negative slopes. The line at the right represents a large resistor used to measure floating potential. Its intersection with the *I . V* curve is near *V*f. Since the *I . V* curve varies about *I*sat over a voltage range of about *T*eV , its effective impedance there isabout *T*eV /*I*sat. Very approximately, then, *R* should be much larger than this value to measure *V*f.

**C. RF compensation**

Langmuir probes used in rf plasma sources are subject to rf pickup which can greatlydistort the *I . V* characteristic and give erroneous results. ECR sources which operate in the microwave regime do not have this trouble because the frequency is so high that it is completely decoupled from the circuitry, and the measured currents are the same as in a DC discharge. However, in rf plasmas, the space potential can fluctuate is such a way that the circuitry responds incorrectly. The problem is that the *I . V* characteristic is nonlinear. The .*V*. is actually the potential difference *V*p - *V*s , where *V*p is a DC potential applied to the probe, and *V*s is a potential that can fluctuate at the rf frequency and its harmonics. If one displaces the *I . V* curve horizontally back and forth around a center value *V*0, the average current *I* measured will not be *I*(*V*0), since *I* varies exponentially in the transition region and also changes slope rapidly as it enters the ion and electron saturation regions. The effect of this is to make the *I . V* curve wider, leading to a falsely high value of *T*e and shifting the floating potential *V*f to a more negative value.

**F. Tests of collisionless theories**

**1. Fully ionized plasmas**

The first test of the BRL theory was done in a Q-machine, a fully ionized potassium plasma at 2300K, by Chen et al.21. Though there was a strong magnetic field, the ion Larmor radii were large enough that the ion current was not affected by it. Both cylindrical and spherical probes were used.

**2. High density rf plasmas**

The situation is entirely different in partially ionized rf plasmas. In Fig. 31, four probe curves were obtained in rf discharges of different density; i.e., different ξp. Each was analyzed using OML, BRL, and ABR theory. The .Hiden. density was obtained automatically by software using OML theory and differs from the .OML. density only in the estimate of *KT*e. One sees that the ABR theory gives too low a density, and the BRL theory too high a density, except at low densities, where BRL converges to OML, as it should. Figure 32 shows that *I*2 varies linearly with *V*p at high density, and both OML and ABR agree with this slope, though different *n* has to be assumed. The BRL theory, however, predicts a more saturated curve. Comparison between theories is shown clearly in Fig. 33. in which *n* is varied by increasing the discharge power. It is seen that BRL predicts too high a density, and ABR too low a density, and the disagreement can be larger than a factor 3. Fortuitously, the geometric mean seems to agree with the correct density, as measured with microwaves.

**V. SPECIAL TECHNIQUES**

**A. Double probes and hot probes**

When *V*s fluctuates slowly, one can use the method of double probes, in which two identical probes are inserted into the plasma in close proximity, and the current from one to the other is measured as a function of the voltage difference between them (*c.f.* Chen, *loc.* *cit.*). The *I . V* characteristic is then symmetrical and limited to the region between the *I*sat.s on each probe. If the probe array floats up and down with the rf oscillations, the *I . V* curve should not be distorted. However, it is almost impossible to make the whole two-probe system float at rf frequencies because of the large stray capacitance to ground. Even if both tips are rd compensated, the rf impedances must be identical. Nonetheless, many industrial plasmas have no contact with a grounded electrode, and a double probe has to be used, sometimes successfully. Hot probes are small filaments that can be heated to emit electrons. These electrons, which have very low energies corresponding to the *KT* of the filament, cannot leave the probe as long as *V*p - *V*s is positive. As soon as *V*p - *V*s goes negative, however, the thermionic current leaves the probe, and the probe current is dominated by this rather than by the

ion current. Where the *I . V* curve crosses the *x* axis, therefore, is a good measure of *V*s. The voltage applied to the filament to heat it can be eliminated by turning it off and taking the probe data before the filament cools. One can also heat the probe by bombarding it with ions at a very large negative *V*p, and then switching this voltage off before the measurement. In general it is tricky to make hot probes small enough. For further information on these techniques, the reader is referred to the chapter by Hershkowitz (*loc. cit.*).

**B. Capacitively coupled probes**

Though most laboratory experiments are done in an inert gas like argon or helium, rf plasmas used in industry have reactive gases, which can wreak havoc on a Langmuir probe. A common problem is that the probe surface becomes coated with an insulating layer. Booth et al28. have devised a transient probe to circumvent this problem. The circuit is shown in Fig. 53a. A large rf pulse is applied through the back-to-back diodes and external capacitor Cx to a coated flat probe. The equivalent circuit is shown in Fig. 53b, where Zsh is the sheath impedance, Cf is the capacitance of the film across which the potential drops from Vsurf to Vc, and the Cp.s are stray capacitances. The rf pulse applies a negative dc voltage to the film surface by the sheath rectification effect. After the rf is turned off, this voltage decays through Cf and Cx, providing a probe bias sweep. The instantaneous *V*p is measured at C with a highimpedance probe. The current is measured with the resistor R. Fig. 53. Circuit for transient flat probe .

With the proper value of Cx, an entire *I . V* curve can be swept out in a few milliseconds. As the film grows in thickness, Cf decreases, and the probe *I . V* will decay at a faster rate, as shown in Fig. 54. Cx must be adjusted accordingly. When the film becomes too thick, the sweep will be too fast for the sheath to come to equilibrium. Figure 5 shows a normal ion characteristic obtained with this technique. However, a guard ring (Fig. 11) must be used and adjusted properly. Figure 56a shows the effect of the guard ring, and Fig. 56b shows that the *I . V* curve behaves properly with pressure.

**Abstract:**

**The Adaptability of Langmuir Probes to the Pico-Satellite Regime.**

by Andrew J. Auman,

The purpose of this thesis is to investigate whether it is feasible to use Langmuir probes on pico-satellites flying in low Earth orbit over mid- to low-latitude geographic regions. Following chapters on the expected ionospheric conditions and an overview of Langmuir probe theory, a chapter addressing the difficulties involved with pico-satellite Langmuir probes is presented. Also, the necessary satellite-to-probe surface area requirements in order to achieve confidence in pico-satellite Langmuir probe data, for the orbital regions of interest to this thesis, are stated.

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**Plasma Diagnostics for Laser Driven Waves in a Large Magnetized Plasma**

C. Niemann, E. Everson, C. Constantin, D. Schaeffer, N.

Kugland, P. Pribyl, W. Gekelman, A. Collette, S. Tripathi and S. Vincena

**Abstract**

The interaction of a laser produced plasma with a large magnetized plasma is studied with various plasma diagnostics. We discuss the theory, design, and construction of three types of diagnostics: Langmuir probes, Mach probes, and B. probes. A perpendicular probe geometry allows data collection extremely close to the target, including inside a diamagnetic bubble formed by the laser blow off. Data and some preliminary analysis is presented for all three diagnostics.

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**Understanding Langmuir probe current-voltage characteristics.**

Robert L. Merlinoa

I give several simple examples of model Langmuir probe current-voltage\_I-V\_ characteristics that help students learn how to interpret real I-V characteristics obtained in a plasma. Students can also create their own Langmuir probe I-V characteristics using a program with the plasma density, plasma potential, electron temperature, ion temperature, and probe area as input parameters. Some examples of Langmuir probe I-V characteristics obtained in laboratory plasmas are presented and analyzed. A few comments are made advocating the inclusion of plasma experiments in the advanced undergraduate laboratory.

**Diagnosing pure-electron plasmas with internal particle flux probes.**

J. P. Kremer, T. Sunn Pedersen, Q. Marksteiner, R. G. Lefrancois, and M. Hahn

Techniques for measuring local plasma potential, density, and temperature of pure-electron plasmas using emissive and Langmuir probes are described. The plasma potential is measured as the least negative potential at which a hot tungsten filament emits electrons. Temperature is measured, as is commonly done in quasineutral plasmas, through the interpretation of a Langmuir probe current-voltage characteristic. Due to the lack of ion-saturation current, the density must also be measured through the interpretation of this characteristic thereby greatly complicating the measurement. Measurements are further complicated by low densities, low cross field transport rates, and large flows typical of pure-electron plasmas. This article describes the use of these techniques on pure-electron plasmas in the Columbia Non-neutral Torus \_CNT\_ stellarator. Measured values for present baseline experimental parameters in CNT are \_*p*=−200±2 V, *Te*=4±1 eV, and *ne* on the order of 1012 m−3 in the interior.*.*

**Plasmon-Coupled Fluorescence Probes: Effect of Emission Wavelength on Fluorophore-Labeled Silver Particles**.

Jian Zhang, Yi Fu, Mustafa H. Chowdhury, and Joseph R. Lakowicz\* *, 2008*

We examined the emission intensity and wavelength of 40 nm diameter silver particles covalently coated with organic fluorophores with different absorption and emission wavelengths. The objective of this study is to use the interactions of fluorophores with the plasmon in the metal particles to create the brightest possible probes. We refer to the complexes as plasmon-coupled fluorescence probes (PCPs). The fluorophores were separated from the metal cores by 10 nm long polymer backbones. The fluorescence was observed to be enhanced for seven fluorophores with emission wavelength from 450 to 700 nm. The enhancement efficiency was shown to approximately increase with long wavelengths for the silver particle-bound fluorophores. When comparing a single fluorophore free in solution and bound to the silver particle, the emission intensity increases 3- to 17-fold. The relationship between the enhancement efficiency and loading number of fluorophore on each silver particle was studied to optimize the conditions for PCP brightness. Compared with the free single fluorophores in the absence of metal, the optimized single labeled silver particles were even more than 1000- fold brighter, showing their potentials in the applications of sensitive clinical and biological assays.

**The use of Langmuir probe for diagnostics of flame Quenching.**

Marc Bellenoue1, Sergei Labuda1, Maxime Makarov2, Julien Sotton1

Electrical properties of flame are studied intensively already almost one century. The interest to ionization processes in combustion front was stimulated e.g. by an attractive idea to use probe signal for combustion diagnostic. Since in the flame charged particles (ions and electrons) are produced, the combustion front can be considered as high pressure plasma. Insertion of an electrical probe in combustion zone could, in principle, yield information on the combustion conditions. Although ion sensing is one of the cheapest and most simple methods for monitoring of combustion event in a spark engine, but still the physical processes of ionization current formation are not fully understood, although there are a number of probe theories trying to explain the evolutionof probe current at different conditions (see [1] among others). These theories are based on Langmuir probe theory adapted to the diagnostics of high pressure plasmas. Because flame behaviour near the probe surface is affected by flame/wall interaction, we supposed that namely process of thermal flame quenching on the surface of probe electrode controls the probe current. In this paper a simple model of ion current to Langmuir probe surrounded by combustion plasma is proposed.

Model taking into account the thermal flame quenching on the surface of probe electrode is proved by experimental data of probe current variation with pressure for methane/air mixtures of different equivalence ratio. Experimentally demonstrated that probe current-voltage characteristics (CVC) is affected by the phenomenon of flame quenching on the probe surface

**Langmuir probe study in the nonresonant current drive regime of helicon discharge**

MANASH KUMAR PAUL¤ and DHIRAJ BORA

**Abstract**

. Characterization of the current drive regime is done for helicon wave- generated plasma in a torus, at a very high operating frequency. A radiofrequency- compensated Langmuir probe is designed and used for the measurement of plasma parameters along with the electron energy distributions in radial scans of the plasma. The electron energy distribution patterns obtained in the operational regime suggest that Landau damping cannot be responsible for the e±cient helicon discharge in the present study. A typical peaked radial density pro¯le, high plasma temperature and absence of an appreciable amount of energetic electrons for resonant wave{particle interactions, suggest that the chosen operational regime is suitable for the study of nonresonant current drive by helicon wave. Successful and signi¯cant current drive achieved in our device clearly demonstrates the capability of nonresonant current drive by helicon waves in the present operational regime.