Debye size microprobes for electric field measurements in laboratory plasmas

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Microelectromechanical systems (MEMS) have led to the development of a host of tiny machines and sensors over the past decade. Plasma physics is in great need of small detectors for several reasons. First of all, very small detectors do not disturb a plasma, and secondly some detectors can only work because they are very small. We report on the first of a series of small (sub-Debye length) probes for laboratory plasmas undertaken at the basic Plasma Science Facility at UCLA. The goal of the work is to develop robust and sensitive diagnostic probes that can survive in a plasma. The probes must have electronics packages in close proximity. We report on the construction and testing of probes that measure the electric field. © 2006 American Institute of Physics. [DOI: 10.1063/1.2198730]

INTRODUCTION

Plasmas by their nature have a hierarchy of size and time scales. The relationship between these interaction scales with respect to turbulence and heat transport is not understood. To study this one needs diagnostics that operate at the smallest scales of import in plasma, and this is where the revolution- ary detectors, which can only be constructed with microelectromechanical system (MEMS) techniques, will make their mark. The electric field, for example, is a fundamental quantity which is generally not correctly measured. The electric field \( \mathbf{E} = -\nabla \phi - \mathbf{A}/c \) at low frequencies and for electrostatic phenomena can be approximated by the gradient of the potential. The accepted way to use a probe to measure the potential in a plasma is to sweep the characteristic Langmuir \( I-V \) curve and find the inflection point at the beginning of electron saturation. This is identified as the voltage at which the probe tip is at the same potential as that of the plasma and there is no sheath around the probe. If this is done for two closely spaced probes, subtracting the results gives the average electric field between them. A sheath several Debye lengths in size [the Debye length is \( \lambda_D = \sqrt{kT_e/\pi n_e} = 743 \sqrt{T_e(eV)/n(cm^{-3})} \text{ cm} \)] and a presheath larger than that are present at all other probe bias potentials. The floating potential is easier to measure; at this voltage there is no net current drawn to the probe, although the probe circuit must have a large input impedance relative to \( T_e/i_{i,sat} \) where \( T_e \) is the electron temperature in eV and \( i_{i,sat} \) the ion saturation current. Often the difference between the floating potentials of two probe tips is used in the hope that it is somehow proportional to \( \mathbf{E} \), particularly when rapidly fluctuating quantities are desired and the swept technique cannot be used. To derive an electric field from the floating potential one must assume that it is related to the plasma potential in a fixed way. However, since electron current completely dominates the floating potential, even a small deviation from a Maxwellian electron distribution can have a profound effect on the value of the floating potential. Quite often in the presence of localized currents or intense waves it has been observed using swept probes that the floating and plasma potentials have nothing to do with one another. It is our opinion that differences in the floating potential should never be used as an \textit{a priori} measurement of the electric field.

The problem with using the floating potential to derive electric fields arises because of this Debye scale shielding. Such a probe will record the potential on its surface, not the potential of the plasma \( 10-20 \) Debye lengths away. The relationship between the measured potential and what is actually going on in the bulk plasma is the subject of many theories, and in a magnetic field they are dubious at best. Furthermore, any probe will actually disturb the plasma if it is significantly larger than the Debye length and, in the case of magnetized plasma, the electron gyroradius, \( r_{ce} = \sqrt{kT_e/eB} = 2.38 \sqrt{T_e(eV)/B(G)} \) cm. Objects larger than \( r_{ce} \) will disturb flux tubes defined by electron trajectories. The ion gyroradius is a factor of \( \sqrt{m_i/m_e} \) larger, and probes larger than this will disturb flux tubes defined by ion trajectories.
the advent of this machine, basic plasma studies of waves and instabilities have been undertaken in unprecedented detail. Most measurements are made with macroscopic probes and rely upon the control of shot reproducibility to make measurements such as those shown in Fig. 1(b). Despite the size of the plasma most data are acquired with only one probe in the entire machine. This is a tolerable situation when repetitive processes are studied. For example, the data in Fig. 1(b), showing a low amplitude (linear) Alfvén wave, were acquired at 16 000 spatial locations, and took 4 weeks and over $1 \times 10^6$ “shots” to acquire. Plasma is an inherently nonlinear medium and can become turbulent under many conditions. When this occurs the phenomena are not repeatable and one must employ either correlation techniques that are either time consuming and somewhat limited or that require a large array of probes (which using existing techniques will usually disturb the plasma).

We must build detectors smaller than the scale size at which (a) the ionized particles behave collectively, i.e., the Debye length $\lambda_D$, and (b) the flux tubes become affected, i.e., the electron Larmor radius $r_{Le}$. On shorter scales objects inserted into the plasma are essentially invisible to the plasma, and a probe constructed on this scale can be used to record the true plasma electric field. If it is sensitive enough it can also record the statistical fluctuations of particles within the Debye sphere.

In space plasmas (rocket and satellite probes) these lengths can be many meters, and superb ion and electron distribution function measurements have been achieved. In space, however, an experimentalist has no control over the environment or experimental conditions, and one measures interesting phenomena only by chance when the spacecraft passes through them. Furthermore, there are, of course, many phenomena of terrestrial interest that do not occur where spacecraft fly.

In contrast to the situation in space, these lengths are quite short in almost all laboratory plasmas. In LAPD the Debye length $\lambda_D$ varies from 20 to 200 $\mu$m, and the electron gyroradius $r_{Le} = 20–100$ $\mu$m. Anything more complicated than a single tip requires the use of MEMS technology since complex objects this small cannot be made reliably by hand under a microscope. Diagnostic tools useful in controlled laboratory experiments, which can measure plasma potential, electric fields, and the electron distribution function on a microscopic scale, will result in a sea change in plasma physics. In theory it would be possible to put thousands of sub-Debye length scale sensors in plasma and not disturb it. In this article we describe the first attempts at such probes for measuring the electric field; other types of probes are under development and will be discussed in future papers.

One observed feature of satellite measurements of electron density in space has been a characteristic solitary blip referred to as an electron solitary structure (ESS). While the spacecraft measurement locus is of necessity only one dimensional, with ambient plasma being sampled only along the satellite’s trajectory, these are believed to represent long-lived “electron holes”—a phenomenon arising in the spatial and velocity distributions of the electrons. Heuristically, an electron hole may be thought of

A second technique to measure the plasma potential is with the use of emissive probes. These emit electrons, usually thermionically, at roughly the electron saturation current to work properly. These probes function well at low densities, but cannot emit sufficient current to work in many plasmas of interest in the laboratory.

An example of such a laboratory plasma is the Large Plasma Device (LAPD) (see Fig. 1). The machine produces a plasma column of 18 m in length and 60 cm in diameter. The axial magnetic field can be as high as 3.5 kG and may be varied along the device length. Ten independent power supplies provide the current to the magnets. The machine has unprecedented access, having over 450 diagnostic ports. More than 60 of these have vacuum interlocks through which probes can be introduced or withdrawn while the machine is running. The plasma is pulsed at 1 Hz, with each discharge typically lasting 10 ms. The plasma is quiescent, with $\Delta n/n \approx 3\%$, and is highly reproducible from shot to shot. The machine can run for up to 4 months, 24 hours a day before the electron beam source needs to be reconditioned. Presently this machine is available for use by the plasma physics community under the auspices of the Basic Plasma Science User Facility (http://plasma.physics.ucla.edu/bapsf). With

![FIG. 1. (Color online) (a) LAPD machine at UCLA. The plasma column is 17 m long and 60 cm in diameter. Magnetic fields are 0.5–2.5 kG. The density of the fully ionized plasma $n_i = 5 \times 10^{13}$ cm$^{-3}$, $0.25 \leq T_e \leq 15$ eV, $T_i = 1$ eV. The experimental repetition rate is typically 1 Hz. Volumetric data are acquired by moving probes from position to position on a plane and then removing the probe and putting into another axial port through the pump down valves. (b) The magnetic field of a shear Alfvén wave measured at 30 000 spatial locations. The wave is moving from right to left at $v = 10^7$ cm/s.](http://plasma.physics.ucla.edu/bapsf)
as a positively charged region, typically of Debye length scale, surrounded by an orbiting cloud of electrons that neutralizes the positive charge as seen from a distance greater than several Debye lengths. The Vlasov equation will support this solution,\textsuperscript{12,13} as the electrons oscillate about this positive “nucleus,” they spend more time at the turning points of their orbit, i.e., the apex, than they do passing through the charged region where they have the highest kinetic energy. Once established, such structures can theoretically persist for times much longer than the inverse plasma frequency. These ESSs exist in the Langmuir wave regime and can arise as a nonlinear final state of Langmuir turbulence. Since these structures exist on a Debye length scale, they have been observed in the laboratory only in very low-density plasmas.\textsuperscript{14} In a higher-density plasma such as in the LAPD the characteristic size of these holes is less than 0.05 mm. A second challenge for a laboratory instrument design is that it must have a rapid temporal response. These structures have been observed by spacecraft to move at roughly half the electron thermal speed, which in the LAPD structures have been observed by spacecraft to move at 0.05 mm. A second challenge for a laboratory instrument design is that it must have a rapid temporal response. These structures have been observed by spacecraft to move at roughly half the electron thermal speed, which in the LAPD is $5 \times 10^7$ cm/s. The scale size of wave phenomena and most likely the structures that might accompany them become smaller at higher frequencies. As an example, electron cyclotron waves transverse to the local magnetic field have wavelengths which can be comparable to the electron gyroradius, of order 100 $\mu$m in the LAPD.

Measuring the electrostatic component of such structures and waves requires that the probe be smaller than the Debye length and probe tips situated on the order of one Debye length apart. The number of electrons displaced from the estimated ESS volume of $\lambda_D^3$, in the LAPD plasma, is typically less than $1 \times 10^9$, i.e., on the order of 0.1 pC or less. Constructing a functioning probe on this scale and sensitivity is difficult. Electronics must be installed very close to the probe head, stray capacitance must be minimized, and for typical Debye scale structures the amplifier must ideally have a subnanosecond response time.

We discuss the design and implementation of two types of microprobes. The first type can be made by hand and assembled under a microscope. The second type was grown by MEMS techniques in a cleanroom. Both probes use the same electronics.

**CAPILLARY GLASS PROBE**

We have constructed probes from capillary glass tubes, pulled to a fine tip. Two types of probes have been constructed. In the first, simple glass capillaries were pulled and bent by hand over a propane flame. Tips approximately 0.2–0.3 mm in diameter could be reproducibly manufactured; by pulling sideways as well as apart these tips could be made to have a bend as well as narrowing; such tips are shown in Fig. 2. In a second version, the capillary glass used was theta glass (so named because the tube is partitioned into two halves, with a cross section that looks like the letter theta). This tube was pulled using an automated Sutter P-87 capillary puller to a repeatable tip size of approximately 50 $\mu$m. Two 25 $\mu$m tungsten wires were inserted into the two halves of the tube and glued at the tip with epoxy. The exposed portions of these wires were separated at the tip by approximately 40 $\mu$m and protruded approximately 100 $\mu$m beyond the epoxy. In either case the glass tubes were painted with conductive silver paint to form a coaxial outer shield for the inner wire.

Although the Sutter puller is not usually used for making tips as large as 50 $\mu$m, it is possible to do so by using many pull cycles. A typical pull cycle works as follows: a hot metal filament provides localized heating, while a constant pull is applied to the two ends of the glass tube. When the glass starts to give and the relative velocity of its two parts reaches a certain level, the program turns off the heating (but not the pulling force) and applies a puff of air. This cycle is repeated as many as 20 times, until the glass ultimately breaks in two.

**MEMS PROBE**

Another type of microprobe was produced using MEMS techniques. In contrast to the glass capillary tips, the probes do not need to be handmade, and the individual tips can be made smaller, more closely spaced, and more reproducible. However, the construction of the tips is both considerably more expensive and much slower than capillary-type probes. Probe tips were produced using a batch-fabrication process shown in Fig. 3. The fabrication process will be described

![Diagram of MEMS Probe Fabrication Process](Image)
more completely in a future publication. Briefly, it begins with a silicon wafer whose only purpose is to provide a platform for the probes to be micromachined upon. As seen in Fig. 3, a 11 \mu m thick film of polyimide is deposited to form the lower insulator and base of the mechanical support for the probe tips. A seed layer consisting of 10 nm of chrome and 30 nm of gold was then evaporated onto the wafer, followed by the deposition and patterning of a 6.5 \mu m thick photoresist film.

The photoresist formed a mold for a 2.5 \mu m layer of gold to be electroplated, and was subsequently stripped with acetone. After stripping the photoresist, the seed layer, originally necessary for the electroplating process, was etched away in order to electrically isolate all the chips on the wafer. This was done using a standard gold etchant, followed by a standard chrome etchant.

The second layer of polyimide was then spun on and cured in a nitrogen oven, forming a structure where gold wires are sandwiched between two insulating polyimide layers. This layer was made to be 13 \mu m thick in order to compensate for the topology of the wires. Next, a 50 nm thick aluminum hard mask was evaporated and patterned using a standard lift-off process. Then, all areas of the polyimide that were left unprotected by the aluminum were etched away in a reactive ion etching (RIE) oxygen plasma. The final fabrication step involved peeling the probe tips off of the silicon substrate, gluing it to the printed circuit board using high temperature superglue, and making wirebond connections from the pads to the board.

A wafer with probe tips of different wire widths and spacings was successfully fabricated. The tip widths ranged from 8 to 20 \mu m and were spaced between 20 and 52 \mu m apart. Pairs of wire tips were separated from other pairs by either 40 or 108 \mu m. Figure 4 shows a scanning electron microscopy image of a set of wire tips that were 20 \mu m and separated by 50 \mu m.

**LOCAL AMPLIFIER**

Because the signals from these probes are small, amplifiers are installed in a small copper box at the plasma end of the probe shaft. A number of fast amplifiers that might be suitable are available. Currently, the one selected for this work is a Texas Instruments THS4303, with a small signal frequency response of 1.8 GHz, voltage gain of 10, and sufficient output current capacity to drive a 100 \Omega load. At high frequencies, this amplifier has rated input noise levels of approximately 5 pA/\sqrt{\text{Hz}} and 2.5 nV/\sqrt{\text{Hz}}. Here, we use the positive gain configuration shown in Fig. 5; with a probe current sensing resistor of 1000 \Omega, the noise figure is less than 5 dB; that is, the total electronics noise is less than three times the Johnson noise from the resistor alone.
Approximately 100 mW is dissipated by each of these amplifier chips; consequently, we have found it necessary to actively cool these probes, since only a minimal amount of heat is conducted by the stainless probe shaft. This is accomplished by the use of a copper tube, 1/8 in. in diameter bent into a hairpin turn and inserted into the probe shaft along with the wires. The ends of the copper tube pass through o-ring penetrations at the end of the probe, and compressed air is circulated through the probe. In addition, we have found that cycling the power to the probe electronics so that it is only on for approximately 20 ms at the time of the plasma shot helps to maintain the temperature of the electronics within usable limits.

These amplifiers have been tested and used with the small Langmuir probes described herein, shown in Figs. 2 and 4. The capillary probes are mounted in the copper box, and this is attached to a probe shaft. This box contains four amplifiers, one for each tip, all in vacuum. The glass capillary tubes are covered with conductive silver paint to form electrostatic shields. Tungsten wires sticking out at the end of each tube are too small to see in this photograph. A copper lid, removed for the picture, is normally bolted to the box, and small holes allow vacuum pump down. The MEMS probes were glued to the circuit board containing eight amplifiers, and the tips protruded about 4 mm past the edge of the copper box; these were connected to the circuit using a wire bonder.

**CALIBRATION TECHNIQUE**

The probes are calibrated using a small antenna circuit, as shown in Fig. 6. The circuit consists of a horizontal wire supported on two 100 Ω resistors in parallel, all soldered to a piece of copper-clad circuit board that forms a “large” ground plane. The center lead of a coaxial cable is connected to the antenna wire, and the shield soldered as closely as possible to the ground plane. For testing, an identical structure (not shown) was constructed about 5 mm away, and used to verify the transmission of such an antenna as a function of frequency (i.e., using identical transmit and receive antennas). At high frequencies, the response of this antenna was flat to within 1 dB up to 2.5 GHz, with an approximate capacitance between the two antenna wires of 0.1 pF. The receive antenna was then removed, and the probe structure mounted in its place, with the copper box fastened directly to the ground plane. Results of using this arrangement to calibrate several of the MEMS probe tips are shown in Fig. 7. In this case, the poor response above about 1.2 GHz is probably due to the probe wiring arrangement internal to the copper box.

**FIG. 5. Amplifier circuit for a single probe tip. The THS4303 provides a voltage gain of 5 into 50 Ω; amplifier frequency response is approximately flat from 5 MHz to 1.8 GHz.**

**FIG. 6. Calibration antenna construction. A small wire is mounted above a ground plane and driven by a coax terminated in 50 Ω.**
RESULTS FROM THE CAPILLARY PROBE

The four tip capillary probe of Fig. 2 was used to search for electron phase space holes. As these structures have been observed by spacecraft to be typically several Debye lengths in size, it was necessary to test the probe in a very low-density plasma. The main oxide coated cathode, which is the source of ionizing electrons in LAPD, was run at a dc of 50 A instead of the usual 5 kA pulsed current. The plasma density, determined by a swept Langmuir probe, was about $5 \times 10^9$ cm$^{-3}$ ($f_{pe} = 630$ MHz) and the electron temperature 6 eV. This yielded a Debye length of 260 $\mu$m, compared to a probe tip spacing of about 400 $\mu$m. Since electron solitary structures are often seen in the presence of drifting electrons a narrow (3 mm diameter) electron beam ($I_b=15$ mA, $V_b=135$ V) located in the center of the plasma was pulsed on, and the microprobe signal digitized at 5 GHz. We collected the data both inside and outside of the beam; an example of data from one and two probe tips is shown in Fig. 8.

The negative going structure apparent in the data moves at $4.4 \times 10^7$ cm/s or about 40% of the electron thermal speed. There also is an abundance of positive going spikes as well as wave-packet-like bursts several cycles in duration. A simple conditional-averaging program was written to bin the structures according to their amplitude. The result is shown in Fig. 9. The electric field, parallel to the background magnetic field, is measured within the electron beam. The field is measured by subtracting the potential between two probe tips. The average full width at half maximum arrived at by averaging over hundreds of these structures is about 10 ns.

Inside the beam there are far more negative going structures than positive ones, as indicated in Figs. 8 and 9. In contrast, amplitudes of negative and positive going potentials...
outside the sheet are nearly equal. Electron-hole-type solitary structures should present as positive spikes. Candidates for the negative spike could be electron clumps or solitons. There is an ongoing investigation as to the nature of these structures but it is clear that this probe is able to detect them. Note that this probe is too large to use in the standard 10\(^{12}\) cm\(^{-3}\) LAPD plasma, where the tips would be separated by about 15 Debye lengths. The MEMS probe described is much smaller and allows for direct display of the electric field.

**RESULTS FROM THE MEMS PROBE**

The MEMS probe was placed in a narrow current sheet (vertical dimension \(h=20\) cm, thickness \(d=4\) mm \(\approx r_c\)) in the center of the LAPD plasma (diameter=60 cm). The current sheet is subject to both low and high frequency instabilities. Plasma flow, transport, and low frequency instabilities in this experiment are discussed in a separate work.\(^{17}\) It is observed that the density in the current sheet drops to about one-half the background density (\(n_{\text{sheet}}=5 \times 10^{11}\) cm\(^{-3}\)). The MEMS probe tips are less a Debye length in width and about two \(\lambda_D\) apart in this plasma. Data were acquired with a fast (8 GHz analog input) oscilloscope with 200 \(\mu\)s data records (32 megasamples) that included the initial switch on of the current sheet. A short temporal history of the perpendicular electric field is shown in Fig. 10, taken at locations inside and outside the current sheet. A difference between this and the previous experiment is obvious. Although there are high frequency waves of substantial amplitude the negative going spikes are absent. There is much less activity outside of the current sheet. The temporal development of the frequency spectrum of waves inside the current sheet is illustrated in a wavelet transform of the time series, shown in Fig. 11 along with the temporal data record. Fourier analysis is not adequate here because the frequency spectrum is a function of time. An inset shows the time series for these data, although the sampling rate of this trace is too dense to distinguish the oscillations visible in Fig. 10.

For reference, the ion plasma frequency is 74 MHz, the electron gyrofrequency is 6 GHz, the ion gyrofrequency 285 kHz, and the lower hybrid frequency approximately 4.6 MHz. There are periodic bursts (also visible in the time trace) that start at the lower hybrid frequency and extend upwards in frequency to \(\approx 10 f_{\text{LH}}\), the whistler wave regime. The wave electric field is quite large, of order 1 V/cm. The probes are small enough and close enough together to make this number believable. The physics of the current sheet is quite complex and will be reported in several publications in the near future.

We have used these examples to illustrate that very small probes can be constructed and will one day provide a wealth of information on high frequency phenomena. By changing the amplifiers mounted near the probes it is possible to directly examine phenomena at the electron plasma frequency in the LAPD (9–10 GHz), provided that fast enough digitizers are made available. The higher frequency probe is in construction and will be used to measure fields in microwave-plasma interaction experiments.\(^{18}\) The next challenge in the construction of these probes is to remove the large copper box containing the amplifiers (visible in Fig. 2), an issue we refer to as the “last inch” problem. In studying a narrow current sheet, for example, one must be careful that only the probe tips enter the region of interest, as the large enclosure for the amplifiers will severely disturb what is to be measured and make three-dimensional measurements as the one shown in Fig. 1(b) impossible. The solution is to “grow” small high frequency charge sensitive amplifiers close to the tips. The amplifiers must provide at least enough gain to deliver the signal to another amplifier which may be inside the vacuum system but well away from the plasma. These are in the planning stage. It is also clear that develop-
ment of probes such as this is highly collaborative and must involve experts on micromachines as well as plasma physicists.

SUMMARY AND DISCUSSIONS

We report on several versions of microprobes, one of which was a MEMS probe that can make local measurements of the electric field in a laboratory magnetoplasma. The probes were calibrated and tested in vacuum and successfully tested in two plasma physics experiments. These initial electric field probes are quite simple in design compared to other probes which we will next attempt. The first is a miniature electron velocity analyzer which will be 100 μm on a side and only 10 μm thick. Future designs must incorporate on-chip amplifiers since the large metal circuit box used in these first tests is the major source of perturbation. (The current version is rather like a hair on the back of an elephant.) Future probes will measure magnetic fields, local pressure, and ion distribution functions.

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