Passive external radio frequency filter for Langmuir probes

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A tunable passive circuit is introduced for radio frequency (rf) filtering of Langmuir probes used to measure plasma properties. The circuit produces a high impedance between the probe tip and ground so that the probe tip follows potential fluctuations in the plasma so that the probe bias voltage with respect to the plasma is constant on the time scale of rf fluctuations. Filtering is implemented at the fundamental frequency (13.56 MHz in this case) and the second and third harmonics. Representative probe traces and electron energy distribution functions from an inductively coupled plasma are presented to demonstrate filter performance. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1376139]

I. INTRODUCTION

Fluctuations in the plasma potential of radio frequency (rf) produced plasmas are well known to interfere with the use of Langmuir probes as a diagnostic tool to measure plasma properties such as plasma density and electron energy distribution functions.[1] Conventional analysis of Langmuir probe I–V traces requires that, for each point on the I–V curve, the current I be measured for a fixed difference in the electrical potential across the sheath between the probe tip and the plasma. If the plasma potential fluctuates while the potential of the probe tip is constant, the current measured is really an average for a range of sheath voltages. Because of the nonlinear characteristics of the sheath, this has the effect of ''smearing out'' the probe trace. Conventional analysis of these distorted probe traces leads to unphysical values of plasma parameters; for example, the apparent average energy determined from distorted probe traces may be substantially higher than the actual average energy. Numerous studies have made use of rf filters to avoid the effects of this distortion. Here we introduce a new variation on filter design with possible advantages for plasmas with plasma potential fluctuations at multiple frequencies.

Several methods exist to combat the effect of rf plasma potential fluctuations on Langmuir probe measurements. The approach we are taking is a new implementation of an established method: electrically force the probe tip to follow the potential fluctuations present in the plasma so that, although both potentials are fluctuating, the sheath potential, which is the difference between the two, is constant so that conventional analysis applies. Godyak and Popov showed that if the amplitude of the fluctuation in the sheath voltage can be kept below a value on the order of the electron temperature, the resulting error in the plasma parameters will be on the order of the uncertainty of the probe technique.[2] The approach of using a ''rf filter'' to force the probe tip to track oscillations in the plasma potential can be explained by considering the probe and its sheath as a voltage divider responding to an oscillating voltage source (i.e., the plasma). A circuit diagram showing the basic elements of typical passive rf filter, along with simplified circuit representations for the plasma and probe bias, is shown in Fig. 1. The oscillating plasma potential $\tilde{V}_p$ is represented as a voltage source, $Z_{\rm sh}$ is the sheath impedance, $Z(\omega)$ is the impedance seen by the probe tip looking toward the probe bias circuit (including the stray capacitance of the probe body, in addition to the rf filter components), V_b is the probe bias voltage, and R is a resistor added to measure the probe current. $Z_{1\,\rm filter}$ and $Z_{2\,\rm filter}$ represent lumped impedances associated with components of the passive rf filter. At rf frequencies, we can expect that the oscillating component of the probe voltage will be

$$\tilde{V}_{\rm probe}=\tilde{V}_p\frac{Z(\omega)}{Z(\omega)+Z_{\rm sh}}.$$

$Z(\omega)$ must be high impedance at the frequency of plasma potential fluctuations (13.56 MHz and its harmonics for our system) relative to $Z_{\rm sh}$ to ensure that $\tilde{V}_{\rm probe}\sim\tilde{V}_p$ and a low impedance at lower frequencies to ensure that the probe I–V curve is accurately captured. $Z(\omega)$ is typically constructed as a ''notch filter'' or series of notch filters, parallel lumped-component (LC) combinations with a LC resonance at the selected frequency.

Often Langmuir probes are mounted on a long shaft that passes through the vacuum wall. Stray capacitance between the wire connecting to the probe and the wall material of the shaft can lead to a substantial capacitance between the two. If the outer shaft is grounded (we use a 0.64-cm-diam grounded stainless steel tube), this creates a low impedance path to ground at high frequencies. A stray capacitance of 40 pF was measured with a capacitance meter on the probe used in this study. The capacitive impedance can effectively short out filters that are added in the most convenient way: external to the probe shaft on the atmosphere side. Various methods have been used to combat this problem. On approach is to place filters *inside* the shaft, as close as possible to the probe tip.[3] This effectively moves $Z_{1\,\rm filter}$ to the probe tip side of $C_{\rm stray}$ compared to the configuration shown in Fig. 1. For

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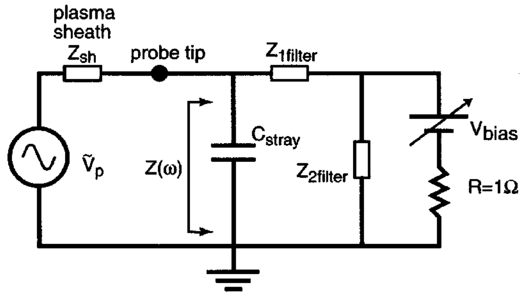

FIG. 1. A simplified circuit model of the probe and plasma. A voltage divider consisting of Z_{sh} (sheath impedance) and $Z(\omega)$ (rf filter impedance, including probe stray capacitance to ground) determines how much of the rf oscillating voltage in the plasma, $\tilde{V}_p$, appears at the probe tip. Ideally, $Z(\omega) \gg Z_{sh}$ to minimize the voltage drop across the sheath.

this method, the filter components must be very small to fit in the probe shaft, and *in situ* tuning of the resonant filters is virtually impossible. Active compensation is another approach: the tip of the probe is driven by a rf voltage source (in addition to the dc probe bias voltage) with a wave form that mimics the fluctuations in the plasma potential.[4,5] It may also be possible to reduce the production of plasma potential fluctuations to a level sufficiently low that they do not interfere with Langmuir probe operation. For example, Godyak, Piejak, and Alexandrovich describe an inductively coupled plasma in which potential fluctuations are suppressed through the use of a Faraday shield.[6]

II. INSTRUMENT DESIGN AND IMPLEMENTATION

In this article we present an approach in which passive filtering is used external to the probe shaft, but which incorporates the probe stray capacitance into a resonant circuit that produces an overall high impedance to ground. The filter was developed for Langmuir probe measurements in an inductively coupled plasma which exhibited unexpectedly large plasma potential fluctuations, most likely due to capacitive coupling between the induction antenna and the plasma. The plasma is powered by a spiral induction coil driven by a rf current at 13.56 MHz. The chamber is over 60 cm in diameter, with a quartz window opening of over 50 cm and a thickness of 3.6 cm. The height of the chamber is 19 cm. A radially spoked grounded Faraday shield has been included just inside the quartz window for two reasons. The first is to reduce capacitive coupling between the induction antenna and the plasma by shorting out electric field lines associated with the rf voltages on the antenna. Because the entire chamber bottom is an electrode that can be floated and most of the chamber top is quartz and therefore always floating, the Faraday shield was located inside the chamber in order to increase the grounded wall area in the chamber. However, the Faraday shield used was apparently not adequate to entirely suppress capacitive coupling between the antenna and the plasma; potential fluctuations of 20 V peak to peak have been observed in this system. The lower electrode was grounded in the experiments presented here. The shaft of the

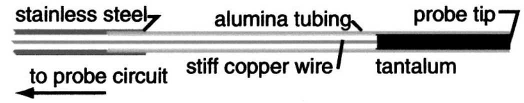

FIG. 2. Tip of Langmuir probe has been designed to reduce capacitive impedance to the plasma.

Langmuir probe passes radially through a sliding vacuum seal on the chamber sidewall. The tip of the Langmuir probe was located approximately in the chamber center.

We also chose a probe mechanical design that produces a relatively low value of Z_{sh}. In a design similar to that described by Paranjpe, McVittie, and Self,[7] the probe tip was constructed to maximize the capacitance between it and the plasma. The probe tip, shown in Fig. 2, is constructed of tantalum rod, 0.32 cm in diameter. The rod is 3.4 cm long, and its full length is covered snugly with an alumina tube of outer diameter 0.48 cm, except for the flat end which is flush with the end of the alumina tube and serves as the probe tip. The capacitance through the alumina tube between the probe and the plasma is estimated at about 40 pF. At 13.56 MHz, that corresponds to an impedance of about 300 Ω. The impedance between the probe tip and the plasma consists of the impedance of the exposed tip in parallel with the series combination of the capacitive impedance of the alumina tube and the sheath that surrounds it. Estimating the sheath thickness around the (electrically floating) alumina tube to be a few Debye lengths in a high density plasma, we obtain a capacitance of roughly 40 pF, comparable to that of the alumina. The combined capacitance of the series combination is thus approximately 20 pF, corresponding to an impedance of about 600 Ω at 13.56 MHz. As the probe bias voltage increases toward the plasma potential, a substantial electron current flows across the sheath which may also contribute to the sheath impedance. This can be treated as a resistance in parallel with the sheath capacitance. As the bias voltage approaches the plasma potential, this resistive component will dominate the sheath impedance, resulting in a value that is small compared to the capacitive impedance of the alumina. In that case, the value of the effective sheath impedance will be reduced, so that the 600 Ω figure can be considered an upper bound.

With the tantalum probe tip, probe cleaning by ion bombardment was employed to greatly improve reproducibility of the probe I–V curves. (Because of the relatively high thermal conductance of the rod, probe cleaning by resistive heating of the probe tip biased to collect electron saturation current was not an option.) Use of a 0.23-mm-diam tungsten wire extension as a cylindrical probe tip emerging from the end of the tantalum rod was also attempted. Such a probe tip is readily cleaned through resistive heating as described above. However, the wire glowed white hot at collection currents less than the electron saturation current, raising concerns that the probe tip was thermionically emitting electrons, which would lead to a distortion of the probe I–V curve.[8] For cleaning, a bias voltage of 100 V is applied to the probe tip while it is exposed to the plasma. Ions from the plasma are accelerated through the 100 V sheath and bombard the probe tip. Ion bombardment sputters contaminants

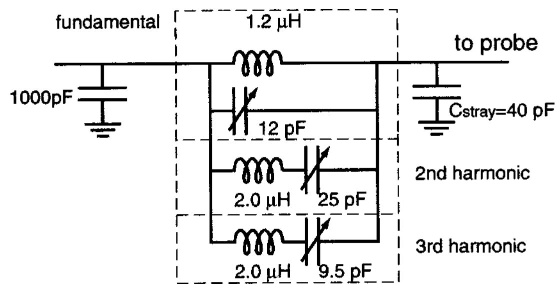

FIG. 3. The rf probe filter produces a high impedance between the probe and ground at 13.56 MHz and its second and third harmonics.

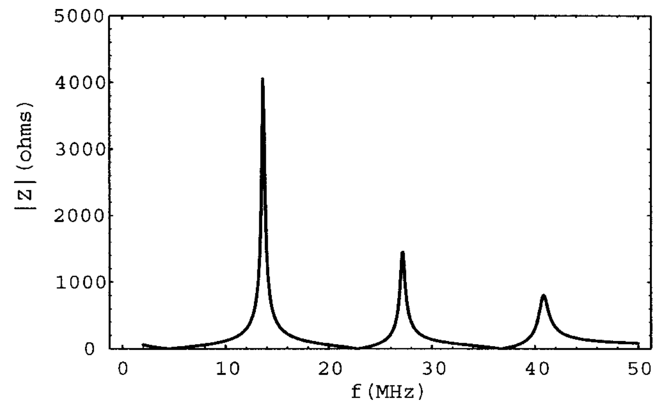

FIG. 4. LC rf filter impedance (including effects of probe stray capacitance) shows peaks at 13.56 MHz and its second and third harmonics.

and oxide developing on the surface which can interfere with the probe operation. The probe is cleaned in this manner for 30 s before each probe sweep, as well as for 1.5 s before each data point is measured.

The filter is inspired by designs by Paranjpe and co-workers and Shimizu, Hallil, and Amemiya.[9] The latter employs transmission line segments as inductive and capacitive circuit components in order to produce high-Q resonances at 13.56 MHz and its harmonics. Both designs employ the probe stray capacitance as part of the circuit. The design of Paranjpe and co-workers uses lumped components, but produces a high impedance only at the fundamental frequency. The filter design of Shimizu and co-workers makes use of coax cable transmission line segments at inductive and capacitive circuit elements which can be tuned by changing the length of the segment. However, this filter design was found to produce a high impedance between the two ends of the filter at the frequencies of interest, but the impedance to ground is too low for our probe. Measurements with a network analyzer revealed an impedance to ground at 13.56 MHz of 333 Ω for the transmission line filter, and impedances at the harmonic frequencies were significantly lower. In order to produce a high impedance between the probe tip and ground at 13.56 MHz and its second and third harmonics, we have implemented a notch filter of a different design from that of Shimizu and co-workers. Using lumped rather than transmission line components, the design compensates for the effects of the probe stray capacitance. The design is shown in Fig. 3. Dashed line boxes indicate the portions of circuit included to add high impedance to ground at the fundamental, second, and third harmonics, respectively. In the absence of the second and third harmonic filters, the design is very similar to that of Paranjpe and co-workers. Because the 1000 pF capacitor introduces a low impedance to ground, the 1.2 μH inductor forms a parallel resonance with the stray capacitance. The 12 pF variable capacitor is added to the first stage of the filter to permit tuning of the resonance to 13.56 MHz. The two additional parallel stages add resonances at the second and third harmonics. The inductors were hand made with relatively heavy copper wire (1 mm diameter) and an air core (lower resistance) to enhance the Q of the resonance.

Values of the inductors and capacitors comprising the filter were selected through an iterative process. Starting with initial guesses of appropriate component values, the impedance of the filter (including the stray capacitance of the probe) versus frequency was computed and plotted to observe the peaks corresponding to the three resonances. Also included in the impedance calculation were resistive elements based on measurements of circuit Q. Component values were then adjusted to shift the frequencies of the resonances to 13.56 MHz and its second and third harmonics, while maximizing the Q of the resonances. Since each of the components affects all three resonances, there is some flexibility in the component values. In addition to maximizing the heights of the peaks, another consideration was to keep the component values in a practical range. The calculated magnitude of the filter impedance is shown in Fig. 4. The impedance at 13.56 MHz is more than an order of magnitude higher than the impedance of the transmission line filter measured using a network anlayzer.

An iterative process was also used to tune the filter to produce a high impedance between probe tip and ground at 13.56 MHz and its second and third harmonics through an iterative process. First, the capacitors were all preset to values close to what was needed, as determined by numerical optimization of the circuit design. A variable frequency sine wave generator was connected to the probe end of the filter through a series of 10 kΩ resistor. Voltages at both ends of the 10 kΩ resistor were monitored on an oscilloscope using 10× oscilloscope probes. Because the capacitance of the oscilloscope probe is non-negligible, the one measuring the voltage at the Langmuir probe end of the filter (V_{test}) must be left in place for the experiments after tuning is completed. Removal of the scope probe would detune the high Q resonances, reducing the impedances at the frequencies of interest by substantial amounts. Sharp maxima in V_{test} were observed as the frequency of the input test signal was swept, corresponding to the three resonances in the circuit. The three resonant frequencies were recorded, and the capacitance values of the three capacitors were tweaked until the resonances shifted to the desired frequencies. This was a bit tedious, but with practice one gets a feel for the effect of the three capacitors on each of the resonances, speeding up the process. Once the filter design was finalized and the filter was tuned, measurements of filter impedance as seen from the probe tip were measured to be 6.4 kΩ at 13.56 MHz, 1.5 kΩ at 27.12 MHz, and 1.2 kΩ at 40.68 MHz.

There is a trade-off associated with the sharpness or Q of

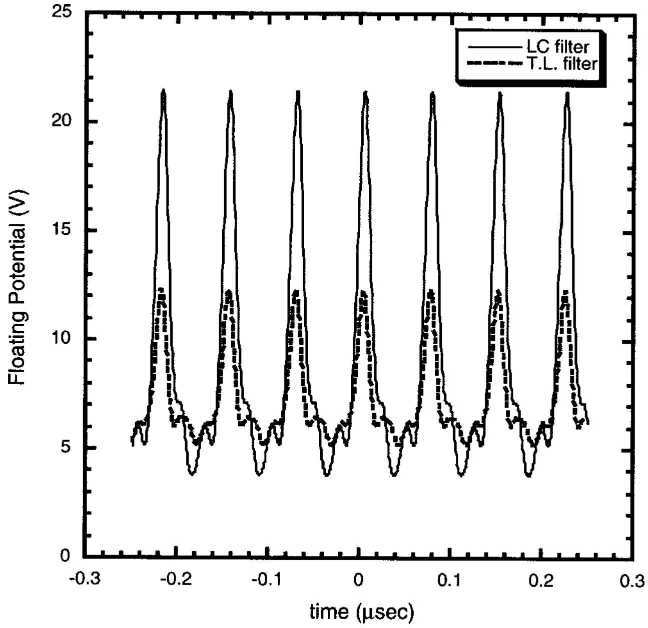

FIG. 5. Langmuir probe measurements of plasma floating potential fluctuations in the inductively coupled plasma systems: 20 mTorr argon and 700 W rf. This comparison between the transmission line (dashed line) and LC (solid line) filters demonstrates the improvement in filter impedance obtained by switching from the transmission line filer to the LC filter. The lower impedance of the transmission line filter leads to the seemingly lower floating potential fluctuation amplitude.

the resonance peaks shown in Fig. 4. The Q depends on the resistive impedance of the circuit elements: the lower the resistance, the higher the Q, and the sharper the resonance. Because our goal is a high filter impedance, a high Q is desirable. However, a high Q also means that the tuning of the circuit is sensitive and potentially subject to detuning which would lead to a significant reduction in filter impedance. Although the tuning process was repeated on a daily basis while measurements were being made, the impedance was found to be quite stable and many times no adjustments were necessary.

Although the filter impedance is lower at the harmonics than at 13.56 MHz, we believe that it is sufficient to provide adequate filtering. First, the plasma floating potential fluctuations are dominated by the fundamental frequency, as can be seen in Fig. 5, so that the degree to which the harmonic components must be suppressed is smaller than for the fundamental. In addition, the capacitive component of the sheath impedance is inversely proportional to the frequency. Since the sheath impedance is lower for the harmonics, a lower filter impedance is sufficient to get the same reduction in the sheath voltage fluctuations at the harmonic frequencies.

Performance of the tunable, lumped element filter was compared with that of a transmission line filter based on the design of Shimizu and co-workers. The transmission line filter consisted of eight cascaded stages, four for the fundamental (and third and fifth harmonics), two for the second harmonic, and two for the fourth harmonic. The filter components were constructed out of 50 Ω RG-58 c/u coax cable.

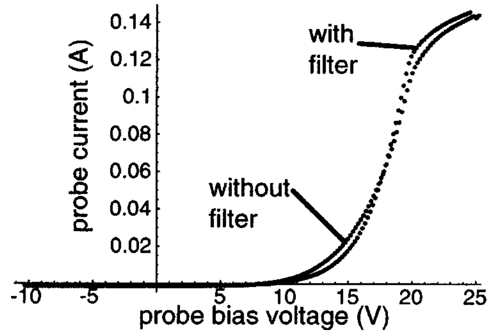

FIG. 6. The improvement in the Langmuir probe I–V traces when the rf filter is used. Curves taken with and without the rf filter are shown for a 20 mTorr argon plasma operating at 700 W. The dots making up the curves represent individual data points.

III. RESULTS AND DISCUSSION

All measurements reported were made in a 20 mTorr argon plasma with 700 W rf power. The probe floating potential (Fig. 5) gives direct information about the ability of the probe to track fluctuations in the plasma potential. Measurements of probe floating potential were made by observing the voltage on the probe end of both the transmission line (TL) and LC filters on an oscilloscope through a 10× scope probe, while the other end of the filter was disconnected from the probe bias power supply and left as an open circuit. The magnitude of the potential fluctuation is nearly twice as high with the new LC filter compared to the TL filter, consistent with a higher impedance $Z(\omega)$ in the circuit depicted in Fig. 1. In the case of the transmission line filter, the low impedance to ground ''loads down'' the measured probe voltage.

Using the amplitude of the floating potential fluctuation as an estimate of the amplitude of the plasma potential fluctuation, we can check, using Godyak and Popov's criterion[2] stated in the Introduction, whether the filter impedance is adequate to avoid unacceptable distortion in the probe I–V curve. Considering the behavior at 13.56 MHz, we compare an estimate of the sheath voltage oscillation with the electron temperature. Treating the sheath/filter combination as a voltage divider, and using the worst case sheath impedance estimate of 600 Ω, along with a filter impedance of 6.4 kΩ and plasma potential fluctuation of 20 V_{p-p} yields a sheath voltage oscillation of less than 2 V_{p-p}. As shown below, the electron temperatures in this system are above 2.5 eV, so the criterion that the sheath voltage oscillation is lower than the electron temperature is satisfied, and we can expect the uncertainties in plasma parameters determined from probe measurements made using the filter will not be dominated by rf distortion.

Probe I–V traces made with and without the filter are depicted in Fig. 6. The presence of the filter results in a probe trace with a sharper transition between ion saturation and electron saturation. In the absence of a high rf impedance between the probe tip and ground, the effect of the rf fluctuations in the plasma potential is to smooth out the I–V curve, so we take this result as another sign that the filter is working as expected.

Electron energy distribution functions (EEDFs) were computed from the second derivative of the Langmuir probe I–V curve, d^2I/dV^2. Smoothing was necessary to suppress signal noise when computing the derivatives. This was achieved by taking the Fourier transform of the curve and processing it with a numerical low-pass filter. In taking the Fourier transform, a modified form of the probe I–V trace is extended beyond the measurement range of bias voltage to crate a periodic function of bias voltage. That is, we assume the same curve repeats over and over, beyond the range of bias voltage over which the trace was originally measured. The curve is temporarily modified to avoid the discontinuity that occurs at the points in bias voltage where neighboring traces meet. To eliminate this discontinuity, the data are subtracted from a straight line passing through the two end points before the transform is performed, and added back after the inverse transform. Otherwise, the smoothing process would result in distortion of the shape of the probe I–V curve in the region of the discontinuity (the beginning and end of the trace) without this step. Derivatives are computed in transform space through multiplication by the appropriate factor.

Figure 7 shows the improvement in Langmuir probe measurements obtained using the LC filter. As expected, Langmuir probe traces made with the LC filter show narrower and more Maxwellian electron energy distribution functions. [A log plot of the electron energy probability function (EEPF) is linear in the electron energy for a Maxwellian distribution.] The value of the effective electron temperature, defined as two thirds of the average electron energy (averaged over the measured EEDF), $T_e(\mathrm{eV})=2\langle E_e\rangle/3$, determined with the new filter is significantly lower than that obtained with the transmission line filter, and other parameters are affected as well. Plasma parameters obtained with the LC filter [Figs. 7(a) and 7(b)]: $V_f=8.8$ V, $V_p=18.7$ V, $n_e=2.5\times10^{11}$ cm^{-3}, $T_e=2.75$ eV. Plasma parameters obtained without the LC filter [Figs. 7(c) and 7(d)]: $V_f=7.8$ V, $V_p=18.7$ V, $n_e=2.1\times10^{11}$ cm^{-3}, $T_e=3.51$ eV.

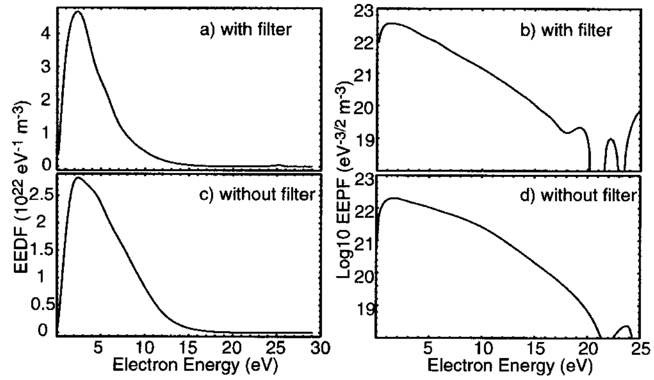

FIG. 7. (a) The electron energy distribution function (EEDF) and (b) the EEPFs for a 20 mTorr argon plasma operating at 700 W when the rf filter is in place, and (c) and (d) the corresponding results with the lower impedance transmission line filter design.

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