Measurement of EEDF's in an RF Plasma

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Abstract: In low pressure, high density plasma reactors, electron energy distribution functions can be non-Maxwellian. In particular, it has been suggested that Landau damping, a kinetic effect, can enhance the RF energy absorption in a helicon source. High-energy electron tails have been reported in helicon discharges in the literature, but the detectors are not always adequately compensated for RF potential fluctuations in the plasma. For instance, we have found theoretically that electron bunches that are phased with the RF, as produced by Landau damping, cannot be seen by Langmuir probes with floating potential compensation [1]. To study these effects and to develop diagnostics for EEDF's in RF plasmas, we have constructed an energy analyzer with enough frequency response to measure the instantaneous electron current and have tested it in RF plasmas generated under controlled conditions with a modulated electron gun and in high density reactor plasmas generated with a Nagoya Type III antenna. Special considerations in analyzer design and measured I-Vcharacteristics under various discharge conditions will be discussed.

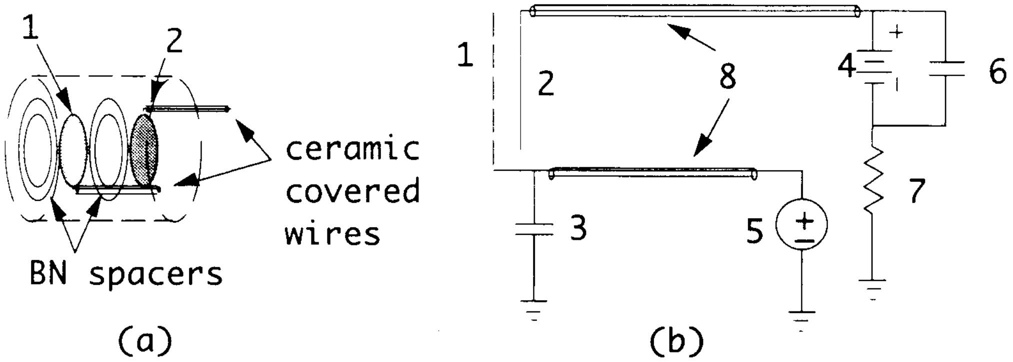
Introduction

RF plasmas present a special set of problems to probe based diagnostics. The biggest is usually the high frequency fluctuation of the plasma potential, which makes the probe sheath voltage drop an unknown quantity and in general makes analysis of the probe characteristic impossible. In addition, the entire integrated volume of the fluctuating sheath will add displacement current to the probe signal, causing further distortion. In the past [2] we have used high impedance mini-inductors built into the probe tip to reduce the RF sheath voltage drop, but the effectiveness of this method is limited to the range of plasma parameters over which we are guaranteed a low ratio of sheath to probe circuit impedance. Recently, another concern that has arisen is the inabilty of this filtering scheme to detect fast variations in the EEDF, which have been inferred from fast fluctuations of the plasma optical emission [3]. For a true representation of the EEDF the probe would have to have enough frequency response to measure the instantaneous electron current at a fixed phase of the oscillating plasma potential and also be decoupled from the oscillating sheath so that capacitive current is not collected along with the electrons.

We have solved this problem by using a carefully constructed electron energy analyzer to measure the plasma characteristics. The electron collector is held at a fixed bias behind a discriminator grid which has very low impedance to ground, which allows electron current through but protects the collector from picking up displacement current. In addition, the impedance of the signal measuring circuitry can be designed to have high frequency response since stray capacitance that would tend to shunt the fast current signals can be virtually eliminated. And most importantly, using a modulated electron beam generated plasma we can actually test this diagnostic under controlled conditions before it is put to use in the plasma, a procedure that to the best of our knowledge has never been performed on any probe based diagnostic in an RF plasma to date.

Experimental Setup

The energy analyzer consists of a fine tungsten mesh (2000 lpi, 40% transparent) 1/2-inch in diameter positioned 3 mm in front of a tantalum collector plate housed inside a 1-inch diameter stainless steel cylinder. The mesh is biased with a variable DC power supply to provide the retarding field while the collector plate is biased very positive (300V) to collect electrons and repel ions. The mesh is also shunted to the grounded housing of the analyzer with a 10nF capacitor to insure minimal capacitive coupling between the collector plate and the plasma. The circuit for the analyzer is shown in figure 1.



(a) (b)

Figure 1. The physical geometry (a) and electrical equivalent (b) of the electron energy analyzer. The basic components are the (1) discriminator grid and (2) collector plate. The grid is biased with a variable power supply (5) while the plate is biased with a 300V battery (4).. Shunting capacitors (3) and (6) are used to eliminate capacitive pickup through the sheath and give the battery circuit sufficient frequency response, respectively. Also to insure good frequency response both components are fed by 50Ω double shielded coax (8) with the collector terminated in 50Ω at the scope (7).

The analyzer is placed in the center of a 108 cm long 10 cm diameter pyrex vacuum chamber with a base pressure of $3x10^{-6}$ Torr. Both the axis of the chamber and the normal of the discriminating mesh of the analyzer are aligned parallel to an external 0.4 T magnetic field. At the end of the chamber opposite the analyzer there is an electron gun. The gun is a heated tantalum filament with a negative DC bias and grid anode located 2 mm in front of it. The anode can be set to any bias voltage to control the intensity and energy of the electron beam when the gun is fired into vacuum, or the density, temperature and potential of the plasma created when the gun is fired into argon. Also, positioned at the midpoint of the chamber is a Nagoya Type III RF antenna 20 cm in length strapped to the outside. The antenna is driven by a 13.56 MHz variable output generator with power output ≤ 2kW. This type of antenna has been shown in the past [ref] to produce high density argon plasmas at low pressures (p ≤ 10mT). A rough drawing of the experimental setup is shown in figure 2.

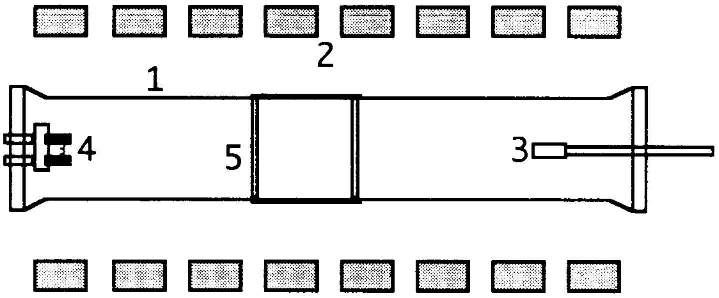
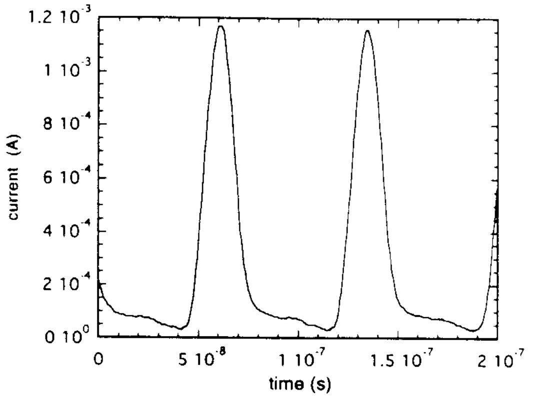


Figure 2. Experimental setup. (1)Pyrex vacuum chamber. (2) Magnetic field coils. (3) Energy analyzer. (4). Electron gun. (5) Nagoya Type III antenna

Current signals from the analyzer are recorded on a 1 GSa/s 250 MHz digitizing oscilloscope. The scope is synchronized to record the maximum and minimum of the current corresponding to the most negative and most positve phases of the oscillating plasma potential.

An example of this current signal taken with the mesh floating is shown in figure 3. As the DC bias of the mesh is varied the max and min signals map out two current-voltage characteristics which are separated on the voltage axis by the peak to peak amplitude of the RF component of the plasma potential.

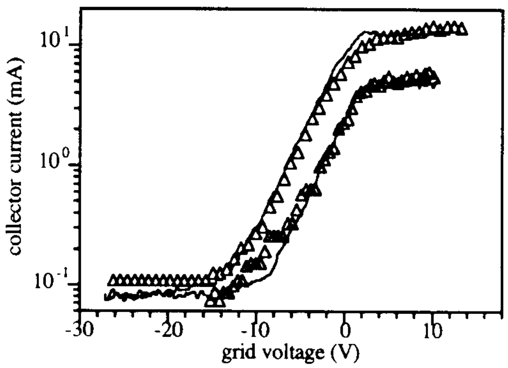
Figure 3. The instantaneous current signal to the analyzer collector plate with the grid floating. The swing in plasma potential gives the effect of rectifying the current signal



Results

The frequency response of the analyzer and effectiveness of the curve reconstruction was tested by first creating a DC electron beam produced plasma, then modulating the plasma at various frequencies by applying the signal from a function generator to the anode. Figure 4 shows the current voltage characteristics of the beam produced plasma under the conditions of steady state (anode DC biased) and high freqency (13.56 MHz) modulation. As predicted, we can see that the modulated curves are duplicates of the DC curves approximately separated on the voltage axis by the peak to peak amplitude of the anode signal, which in this case was set to match the difference of the two DC biases. A plasma was then created by feeding 400W RF power into the antenna with the magnetic field on and off and with the analyzer positioned in the far field and near field of the antenna, respectively. The RF antenna produced plasma had an oscillating component of the potential that was more than 50V peak to peak as measured by a high impedance capacitive probe, causing the separation between the two curves corresponding the max and min phases of the RF cycle to become so large that it was feasible only to rebuild the characterstics corresponding to the minimum plasma potential, since accessing the complimentary phase would mean that half the time the grid would be biased high into the saturation region of the minimum potential curve. Figure 5 shows that the reconstructed current-voltage characteristics are indicative of approximately maxwellian EEDF's, with electron temperatures in close agreement with previous measurements [4]. In light of this and given that the electron-neutral collision frequency is already more than 50 MHz, it appears highly unlikely that we would expect to observe any coherent response of the EEDF to the RF fields as described in [3].

Figure 4: Current voltage characteristics in an electron beam produced plasma with and without modulation. The gun cathode is biased at -100V and fired into 10 mT of Argon gas with a 0.4 T magnetic field while the analyzer is positioned 75 cm away. The solid lines represent the plasma produced with the anode DC biased, while the (Δ) are the reconstructed curves with the anode modulated to the same two extremes at 13.56 Mhz.



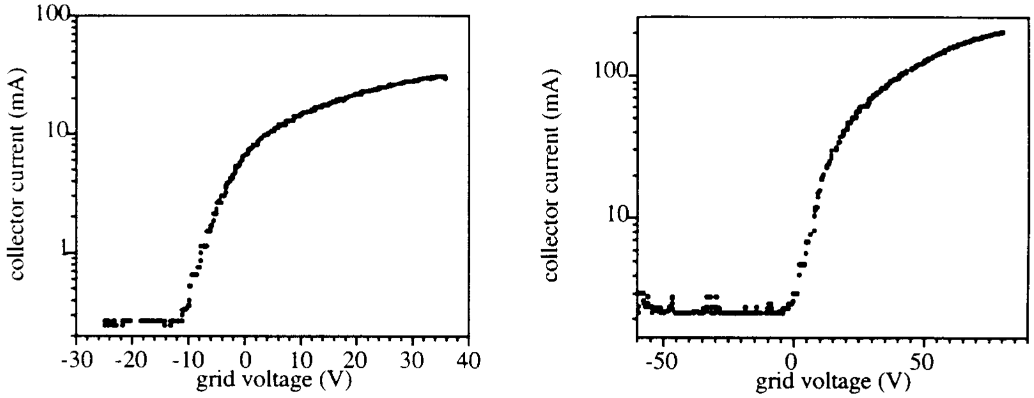


Figure 5. The current voltage characteristics of the RF plasma. The right curve was measured directly under the antenna with the magnetic field off, the left 30 cm away with the magnetic field on, showing maxwellian EEDF's over the resolution of the anlyzer with electron temperatures of 3 and 5 eV, respectively. Both plasmas were generated with 13.56 Mhz, 400W RF power in 5 mT argon.

Conclusions

We have demonstrated a method of obtaining the EEDF of an RF plasma with an electron energy analyzer capable of measuring the instantaneous current at a fixed phase of the RF cycle, thus eliminating the distortion that may be caused by the fluctuating plasma potential without requiring any feedback mechanisms or compensation. We have found the characteristics to be in strong agreement with previous measurements taken with RF compensated probes. Given the high collision frequency associated with these plasma parameters (60MHz) we would not expect to see the EEDF respond to the RF fields in a coherent fashion save for the shifting of the potential. In future work improvements to the energy analyzer would be smaller size so that regions closer to the antenna could be probed when the magnetic field is on without significant disturbance to the plasma and better energy resolution to measure the more energetic electrons of the EEDF.

References

1. D.D. Blackwell and F.F. Chen, Bull. Amer. Phys. Soc. **40**, 1771 (1995)
2. I.D. Sudit and F.F. Chen, Plasma Sources Sci. Technol. **3**, 162 (1994)
3. A.R. Ellingboe et al., Phys. Plasmas **2**, 1807 (1995)
4. D.D. Blackwell, M.S. thesis, University of California at Los Angeles (1994)