Electrical probes for electron energy distribution function (EEDF) measurements in low pressure hydrogen plasmas

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The EEDF is of special interest in low pressure plasmas and often measured using the conventional Langmuir probe technique, which relies on the numerical analysis (second derivative) of the V/I characteristics. In order to measure the second derivate directly, the Boyd-Twiddy [1] method was used, where a voltage ramp is superimposed by an AC modulated signal. The current at the modulation frequency directly yields the EEDF. Measurements were carried out at ECR and ICP discharges, operating in a similar pressure and plasma parameter range. The results show a good agreement between the Langmuir probe and the Boyd-Twiddy technique, whereas the Boyd-Twiddy method is much less noisy. In addition, in ICP discharges the RF disturbance is automatically filtered, using the modulation technique.

1. Introduction

For process optimisation the knowledge of the EEDF, which is generally non-Maxwellian in low pressure plasmas, is of particular importance.

Druyvesteyn [2] showed that the EEDF is proportional to the second derivative of the V/I characteristics obtained by a Langmuir probe. However the dynamic range is limited and electron currents become very small at higher energies (typically E>10eV for low temperature plasmas). Therefore, the second derivative from numerical techniques gets inherently noisy.

In order to solve this problem, R.L.F. Boyd and N.D. Twiddy introduced a technique for direct measurement of the second derivative in 1959 [1]. For this direct measurement the voltage ramp is superimposed with a square wave modulated sine wave. The current at the modulation frequency directly yields the second derivative. Since the frequency for the modulation is freely selectable, this method can also be applied in plasmas where a conventional Langmuir probe has a strongly disturbed V/I characteristics (DC part) and provides reliable results [3,4,5]. In this paper the conventional Langmuir probe and the Boyd-Twiddy method are both applied to low pressure (p<10Pa) hydrogen discharges.

2. Theory

The EEDF $N(E)$ is correlated with the electron energy probability function $f(E)$ and depends on the second derivative of the V/I characteristics, measured with a langmuir probe system:

$$N(E)=\sqrt{E}\,f(E)=\frac{2}{A\,e}\sqrt{\frac{2\,m_e E}{e}}\frac{d^2 I}{dV^2} \quad . \qquad (1)$$

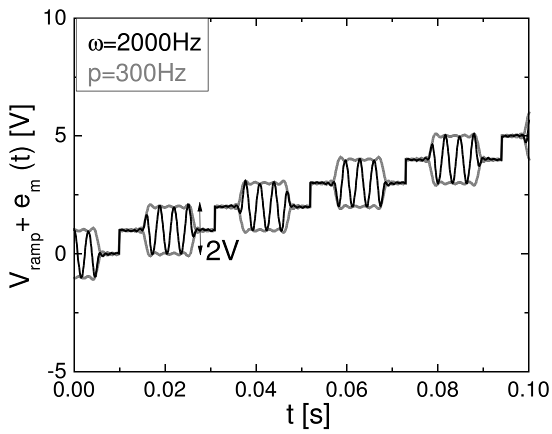

Fig. 1. Example for a modulated signal.

A is the area of the probe and E is the probe voltage with respect to the plasma potential V_p (E=V_p-V).

In the Boyd-Twiddy technique a modulated signal

$$e_m(t)=C\left[\frac{1}{2}+\frac{2}{\pi}(\cos pt-\frac{1}{3}\cos 3\,pt+...)\right]\cos\omega t\,, \qquad (2)$$

is superimposed to the probe voltage V_{ramp} (figure 1). C is the amplitude of the modulated signal with modulation frequency p and carrier frequency ω.

Using Taylor's theorem, it can be shown that the current at the modulation frequency p has only even-order derivatives:

$$i_p=\left[\frac{C^2}{2!}\frac{1}{\pi}f^{''}(V)+\frac{C^4}{4!}\frac{3}{8}\left(\frac{1}{4}+\frac{1}{\pi^2}\right)f^{''''}(V)+\ldots\right]\cos pt, \qquad (3)$$

Neglecting the fourth and higher orders, the EEDF can be directly obtained from the measurement:

$$N(E)=\frac{8\pi}{Ae}\sqrt{\frac{mE}{e}}\frac{i_p(rms)}{C^2}(eV)^{-1}\,cm^{-3}\,, \qquad (4)$$

where i_p is the measured root mean square (*rms*) value of the current at frequency p.

3. Experimental setup

Measurements were carried out in an electron cyclotron resonance (ECR) plasma and in an inductively coupled plasma (ICP). The configuration of the ECR discharge is shown in figure 2. The microwave (f=2.45GHz, P_{max}=1kW) is coupled via a

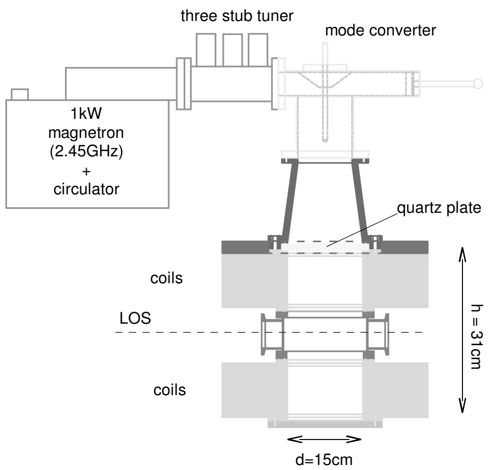

Fig. 2. Setup of the ECR plasma.

three stub tuner and mode converter through a quartz plate into the discharge chamber (*height*=31cm, *diameter*=15cm). The coils generate a homogeneous magnetic field of B=87.5mT, which is in resonance with the microwave. Therefore a homogeneous plasma can be generated in the diagnostic region (LOS), where the probe measurements are carried out. In order to avoid a cut-off, the microwave is introduced on the high field side. This results in a very good coupling of the microwave and thus in a large pressure (p=0.01-20Pa) and power regime (P=30-1000W) for plasma generation. As a consequence the diagnostic methods can be tested in a wide range of electron density (n_e=10^{16}-5×10^{18}m^{-3}) and electron temperature (T_e=1.5-12eV).

The ECR plasma can be operated in pulsed or continuous mode, whereas the ICP (f=1MHz) has a typical pulse length of 6s. In the ICP discharge the plasma is generated in an alumina cylinder with coils (driver) and expands into the source chamber (expansion region). Measurements were carried out at different distances with respect to the exit of the driver. Since the ranges of pressure (p=0.3-0.5Pa), electron density (n_e=10^{17}-10^{18}m^{-3}) and temperature

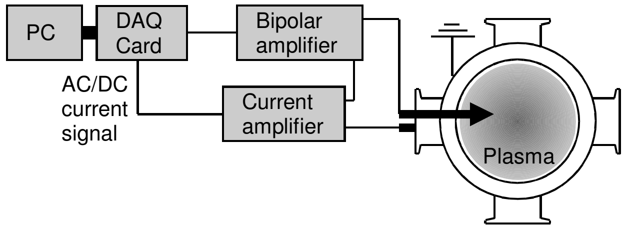

Fig. 3. Setup of the Boyd-Twiddy probe system.

(T_e=1-10eV) of both experiments are similar, the applicability of the methods to different plasma generation mechanisms can be verified. However, due to the RF frequency and the high input power of the ICP (P=60-120kW) measurements with a conventional Langmuir probe are difficult.

Each of the probe systems has its own hardware and software, and is applied simultaneously under well defined discharge conditions. In the ECR plasma the Langmuir probe system uses a low pass filter together with a Blackman filter. Voltage ramps (U= ±70V) were applied between the probe tip and the grounded chamber wall. A stepping motor allows for profile measurements. For the measurements in the ICP discharge, passiv RF compensation is used.

As shown in figure 3 the hardware for the Boyd-Twiddy method consists of a data acquisition card, which is connected to a bipolar amplifier. The same probe tip as for the Langmuir probe was used, consisting of a small cylindrical tungsten wire (*diameter*=50µm, *length*=5mm). In order to measure the conventional V/I characteristics (DC) and the Boyd-Twiddy Signal (AC) at the same time, the AC and the DC currents were separated by low pass and high pass filters. After separation the DC and AC signals were individually amplified and analysed. In order to get the current at frequency p a fast Fourier transformation was applied to the AC current signal.

4. Results

First measurements were carried out in an ECR discharge. In order to compare electron temperatures with results from the optical emission spectroscopy a helium plasma with low electron density (n_e=6×10^{16}m^{-3}) was used. However, the low electron density results in low DC and AC current signals for the probes. Figure 4 shows a good agreement between the EEDFs from a Langmuir probe and from the Boyd-Twiddy method. For better comparison the energy probability functions *f(E)* are plotted in a logarithmic scale.

Both probe methods indicate Maxwellian distributions with temperatures of T_e=11.5eV and

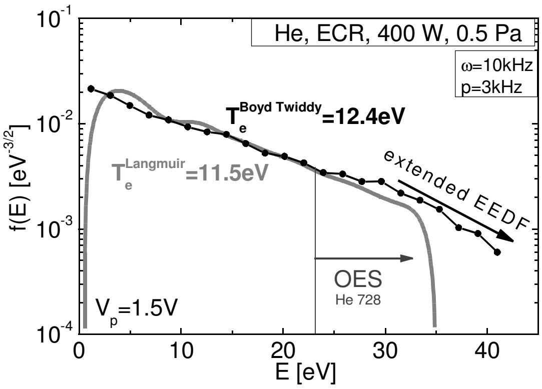

Fig. 4. EEDFs in an ECR plasma.

T_e=12.4eV. The Boyd-Twiddy technique extends the distribution of the Langmuir probe measurement to lower (E<4eV) and higher (E>32eV) energies. The dynamics of the electron energy distribution function obtained by the Boyd-Twiddy technique is thereby limited by the noise at the used modulation (p=3kHz) and carrier frequency (ω=10kHz). Therefore it is important to choose undisturbed frequencies. The temperature from the absolute emission of the HeI 728nm line (T_e≈12eV, E_{thr}≈ 23eV) is in good agreement with the probe measurements.

Figure 5 shows the EEDFs measured in an ICP hydrogen discharge at d=20cm distance from the driver exit. The distribution function from the Langmuir probe is in good agreement with the results from the Boyd-Twiddy technique (typically used frequencies are p=1.5kHz and ω=7.5kHz). Both agree well with a Maxwellian energy distribution of T_e=1.2eV. However it can be seen clearly, that the DC signal was disturbed at lower and higher energies, although a RF compensation was used.

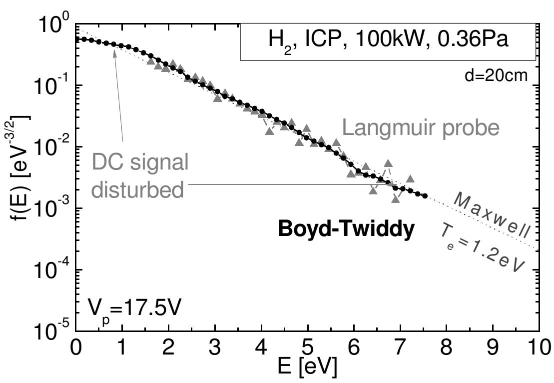

Fig. 5. EEDFs in an ICP hydrogen plasma.

Using another probe head, but without RF compensation, it was possible to measure the distribution functions at different distances from the driver exit. Although the AC and DC signal represent averaged values, the DC signal gets more noisy (figure 6) than the AC signal. The temperature at a distance of d=5cm from the driver exit is T_e=6.6eV and the electron density is about n_e=1× 10^{18}m^{-3}. Thus the current signals measured by the probe systems are high and one expects higher dynamics for the EEDF. However, due to the short distance to the driver (P=80kW) the broadband noise is increased. Therefore all possible modulation and carrier frequencies, which are limited by the bipolar amplifier (f<20kHz) are disturbed. This disturbance limits the dynamics of the electron energy distribution function obtained from the Boyd-Twiddy technique. But the results from the AC signals are still stable and reliable, considering how difficult probe measurements in such high power RF discharges are.

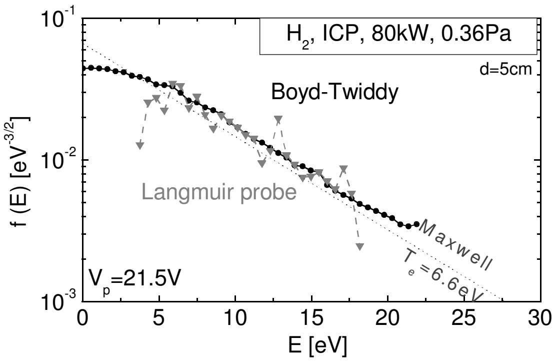

Fig. 6. EEDFs in an ICP hydrogen plasma.

In order to get a temperature profile for the ICP discharge the distance from the probe tip to the driver was varied (figure 7). Since the DC signals are too noisy, only the Boyd-Twiddy distributions are shown. All energy distributions are close to Maxwellian distributions and temperatures between T_e=1.2eV and T_e=14eV are obtained. At a distance of d=1cm to d=17cm the distributions show a strong decrease in electron temperature and are slightly peaked at about T_e=3eV. This can be attributed to the presence of a magnetic filter field in exactly this region, for the purpose to cool down and filter the electrons. In addition it can be seen, that with a closer distance to the driver, the noise increases and therefore the dynamics of the EEDF decreases.

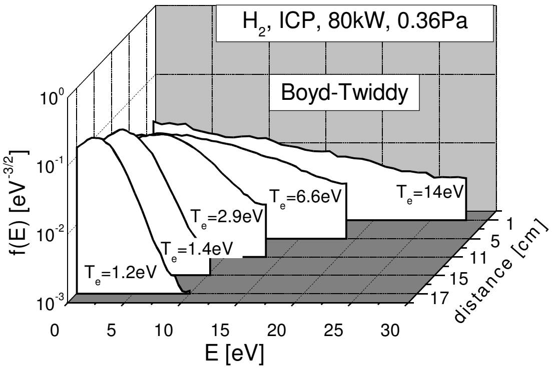

Fig. 7. EEDFs at different distances from the driver exit.

5. Conclusions

EEDF measurements with the conventional Langmuir probe and Boyd-Twiddy method were carried out at ECR and ICP hydrogen discharges. Since the Boyd-Twiddy technique measures the second derivatives directly, the distributions are less noisy than the results from the Langmuir probe, especially in RF plasmas. Undisturbed measurements at free selectable frequencies make it possible to extend the energy range of the distribution functions.

6. References

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