EEDF measurements in plasma expansion region of a high-frequency driven hydrogen discharge

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Abstract. The production of negative hydrogen ions by volume processes depends on the electron energy in the expansion region of a plasma source. The study presents experimental results for the electron energy distribution function (EEDF) obtained by probe diagnostics in this region. Measurements are performed in axial and radial directions at low gas pressures. The results for the EEDF show that its shape changes along the chamber axis because the plasma density and the electron temperature decrease to a nearly constant value in the main part of the expansion chamber. The EEDF is Maxwellian-like with tail up to 40 eV close to the driver. The nonlocal formation of the EEDF is experimentally obtained in expanded plasma.

1. Introduction
The inductive plasma sources are widely used in industrial applications such as surface modifications and etching [1, 2]. These sources consisting of two chambers - driver region and region of plasma expansion - have been recognized as potential negative hydrogen ion beam sources [3]. The negative ion beams are an effective way of producing high energy neutral beams intended for additional heating of plasma in fusion experiments [4, 5]. The driver of the source is region of higher electron temperature plasmas needed for vibrational excitation of the hydrogen molecules $e_{\text{fast}} + H_2(v = 0) \rightarrow H_2(v) + e$ while in the expanding region the plasma with lower electron temperature favours the dissociative attachment (DA) of electrons to the vibrationally excited molecules to produce negative hydrogen ions $e_{\text{slow}} + H_2(v) \rightarrow H^- + H$ [6]. The first of the processes requires a large number of electrons with energy exceeding 20 eV, while for the effective DA electrons with energy around 1 eV are needed. However, the optimization of the conditions for these processes requires detailed study of the plasma parameters and the electron energy distribution in both the driver and the plasma expansion region of the source. The relative abundance of electrons with a given energy is described by the electron energy distribution function (EEDF) and therefore the efficiency of the negative hydrogen ion sources is greatly influenced by the shape of the EEDF. The EEDF determines also the rates of the kinetic processes. As a first step towards optimal conditions (neutral gas pressure and injected power) for negative ion production we have investigated experimentally the spatial variation of the shape of the EEDF in the expansion region of an inductively driven two-chamber plasma source.
2. Experimental set-up
The experiments are performed in a two-chamber inductively driven plasma source [7, 9] schematically presented in figure 1. The high frequency signal at 27 MHz generated by an RF generator (ICOM IC-718) is amplified by an ACOM 2000A linear amplifier and fed through a matching box to a copper coil. The coil consists of 9 turns, closely wound on a quartz tube with an inner diameter of 45 mm and a length of 300 mm. The plasma of the discharge expands in a much larger metallic chamber with an inner diameter of 220 mm and a length of 470 mm. Two movable single Langmuir probes allow for scans in the radial and the axial direction of the chamber. The probes are passively compensated in order to reduce the effect of the high-frequency field on the probe current-voltage (I-V) characteristics. The compensation is obtained by utilizing four resonant RF chokes tuned at the fundamental and the second harmonic of the HF signal and a floating electrode connected through a capacitor to the probe tip [1, 10]. The probe tips are tungsten wires with a diameter of 0.5 mm and a length of 6.0 mm.

![Diagram of the experimental set-up](image)

Figure 1. A scheme of the experimental set-up and the data acquisition system.

The probe measurement system is described in details in reference [11]. In brief, the probes are biased by a high-voltage amplifier which amplifies a linear ramp produced by a ramp generator. The probe current-voltage characteristics are recorded by a digital storage oscilloscope Tektronix TDS360 and then transferred to a personal computer. The probe I-V curves are smoothed numerically by a Savitzky-Golay second order filter. This filter allows noise suppression without distortion in the second derivative of the experimental curve.

The EEDF \( F(E) \) is obtained from the second derivative of the probe I-V curve according to the Druyvesteyn formula [1]:

\[
F[E = e(U_{pl} - U)] = \frac{\sqrt{8m_e}}{e^3S} \sqrt{E} \frac{d^2I_e}{dU^2}.
\]

Here \( m_e \) is the electron mass, \( e \) is the elementary charge, \( S \) is the probe surface area and \( U \) is the probe voltage. For comparison with the Maxwellian distribution it is more convenient to use the electron energy probability function (EEPF) which is connected to the EEDF: \( EEPF(E) = F(E)/\sqrt{E} \). The second derivative is obtained using modified three-point finite difference method. The modification concerns proper treatment of irregularities in the sampled data and adaptive differentiation step [11].

The electron concentration is obtained from the integration of the EEDF. The electron temperature is evaluated from the slope of the EEPF and as a mean electron energy, also. The zero crossing of the second derivative is taken as a plasma potential.
3. Results and discussion

The probe measurements are performed in the expansion region of the source with a distance between consecutive positions $\Delta z = 2$ cm in axial direction and $\Delta r = 1$ cm in radial direction. The axial variation of the shape of EEPF at $p = 10$ mTorr for two values of the power $P = 250$ W and $P = 500$ W is presented in figure 2. The shape of the EEPF close to the driver region shows a presence of electrons with energies up to 40 eV. The electrons with energy above 20 eV are a requisite for effective production of vibrationally excited molecules [6]. The slope of the EEPF exhibits strong increase with the distance from the driver region accompanied by disappearance of the high energy tail after $z \sim 8$ cm. These changes of the shape of the EEPF correlate with the process of plasma expansion in the diffusion chamber investigated recently in argon discharge [7, 8] where the body of the EEPF is Maxwellian. The deviation of the EEDF body from Maxwellian one depends on the ratio between the frequency of electron-electron (e-e) collisions $\nu_{ee}$ and the frequency $\delta\nu_{en}$ of energy transfer where $\delta = 2m_e/M_n$ and $\nu_{en}$ is the frequency of momentum transfer in electron-neutral elastic collisions. The values we calculated for $\nu_{ee}$, $\delta\nu_{en}$ and $\nu^* \ (\text{inelastic collision frequency})$ [12] at $p = 10$ mTorr and $P = 250$ W show that for all axial positions $\delta\nu_{en} \gg \nu_{ee}$. The inelastic collisions are the predominant ones close to the driver. The frequency of momentum transfer in hydrogen is independent on the velocity for electron energies between 3 and 50 eV and the EEDF is close to Maxwellian distribution [13]. For low energy electrons, $\nu_{en}$ is proportional to the velocity. As $\delta\nu_{en}$ is greater than $\nu_{ee}$, the EEPF deviates from the Maxwellian distribution and is similar to the Druyvesteynian one away from the driver [5]. At higher input power ($P = 500$ W), the straight line part of the EEPF becomes longer than that at $P = 250$ W which is due to the increasing of the e-e collisions role in the process of establishing the Maxwellian distribution.

These results are confirmed by the shape changes of the EEPF at neutral gas pressure $p = 20$ mTorr at $P = 250$ W and $P = 500$ W presented in figure 3. At this pressure electrons with energies up to 35 eV exist close to the driver. The shape of the EEPF changes along the axis due to the decrease of the electron temperature and concentration. The transition from Maxwellian to Druyvesteyn-like can be seen in figure 4 for axial positions $z = 10$ cm and $z = 25$ cm at $P = 500$ W. The shape of the EEPF in the energy range 1 - 4 eV deviates both from the Druyvesteynian and the Maxwellian distributions. This distortion is most probably due to plasma potential fluctuations and leads to an underestimation of the absolute value of the plasma density. The axial and radial profiles of the plasma density are obtained at the

![Figure 2. Axial variation of the EEPF at $p = 10$ mTorr (a) $P = 250$ W and (b) $P = 500$ W.](image-url)
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The decrease of the plasma potential from the driver region and remains constant with the change of the HF power. A smooth measure of the electron temperature energy in the entire volume of plasma expansion, the slope of the obtained EEPFs is used as a assumption that the relative values of the measured density are not greatly affected by this effect.

Plasma parameters and their variations along the axis of the diffusion chamber are presented in figure 5 for $p = 20$ mTorr. The electron density $n_e$ is higher at $P = 500$ W and decreases along the axis but $n_e(z)$ has non-monotonic behaviour. In order to compare the mean electron energy in the entire volume of plasma expansion, the slope of the obtained EEPFs is used as a measure of the electron temperature $T_e$. The electron temperature decreases with the distance from the driver region and remains constant with the change of the HF power. A smooth decrease of the plasma potential $V_p$ with $z$ is observed (figure 6), while the floating potential $V_f$ has non-monotonic behaviour. After initial increase of the $V_f$ to distance $z \sim 10$ cm, it decreases slowly together with $V_p$ following the relation $V_p = V_f + 4.3kT_e/e$. These results are in accordance with previous investigations of the spatial variation of the plasma parameters in the same region for wide pressure range [9].

The results from measurements of the profiles of the EEPF in radial direction (at axial

Figure 3. Axial variation of the EEPF at $p = 20$ mTorr (a) $P = 250$ W and (b) $P = 500$ W.

Figure 4. Comparison of the experimentally obtained EEPF ($P = 500$ W, $p = 20$ mTorr) with a Maxwellian and Druyvesteynian probability function (PF): (a) $z = 10$ cm and (b) $z = 25$ cm.
The measured EEPF show a non-local behaviour [1] in the diffusion chamber away from the driver. The reason is the high value of the electron relaxation length \( \lambda_e = \sqrt{\lambda_\epsilon} \sim 40 \text{ cm} \) with respect to the radial \( R/2.4 = 4.58 \text{ cm} \) and the axial \( L/2 = 23.5 \text{ cm} \) diffusion lengths. Here \( \lambda \) and \( \lambda^* \) are the mean free paths for elastic and for inelastic collisions, respectively. In this case the electrons cross the plasma without changes in their total energy \( \varepsilon = E + c\phi \) where \( \phi < 0 \) is the ambipolar potential. The measured EEPF in radial and axial directions shifted by the potential energy \( (c\phi) \) are presented in figure 8a and 8b, respectively. The non-local kinetics of the electrons determine the almost constant value of \( T_e \) in the main part of the diffusion
4. Conclusions
Spatial variations of the EEDF in the region of plasma expansion of a HF driven hydrogen discharge are measured. The EEPF is Maxwellian-like close to the driver and has energy tail up to 40 eV which ensures effective production of vibrationally excited molecules. The Maxwellian shape of the EEPF can change to Druyvesteyn-like because of the decrease of the electron temperature and concentration in the expansion region. The EEDF has weak dependance on the radial position and shows non-local behaviour away from the driver.

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