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Probe measurements of electron energy spectrum and plasma-wall interaction in Helium/air micro-plasma at atmospheric pressure

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Abstract. It is experimentally demonstrated that a wall probe may be a useful instrument for measurement of electron energy spectrum (EES) and the plasma-boundary interaction in a micro-plasma with a nonlocal electron distribution function at atmospheric pressure. The measurements of the EES have been conducted in the plasma of several micro-hollow cathode discharges of differing sizes. The discharges with a flow of Helium gas were exposed to air. Typical results of measurements demonstrate signature of energetic electrons arising due to plasma-chemical reactions. It is experimentally shown that wall probe potential is associated with energetic electrons rather than the ambient electron kinetic energy. The devices may be applicable for developing analytical sensors for extreme environments, including high radiation and high temperatures.

1. Introduction

Electric probes are widely used for measurements of the electron distribution function (EDF) in a plasma [1, 2]. Cylindrical probes are normally used, where a cylindrical rod is inserted into the plasma and acts as the probe. Recently [3, 4] it was demonstrated that a wall probe might be a convenient tool for measurements of the EDF in plasmas with a nonlocal EDF [5]. The wall probe is an electrically isolated part of the volume boundary, serving to collect the current from the plasma for different probe potentials. The wall probe has benefits of greater area (higher sensitivity), absence of a probe-holder (less plasma distortion) and reduced influence of ion current (less distorted measured EDF). Due to constructive reasons, the wall probe (in contrast to a cylindrical probe) can also be more easily used in a micro-scale plasma.

For correct measurements of the EDF, the wall probe area should be much smaller than the plasma boundary area and an appropriate probe theory should be used [2–4]. In this case, the measured EDF from the wall probe would be practically equal to the EDF in the undisturbed (by the probe) plasma. In contrast, if the wall probe is large, the measured EDF (which we will refer as the electron energy spectrum (EES)) may not accurately represent the EDF in the undisturbed plasma as the plasma properties can change during the measurements. Such alternation in a plasma with nonlocal EDF can be smooth [6, 7] or sharp [8], depending on the plasma geometry. Although not ideal, a large wall probe may still be useful for applications where higher sensitivity of the probe measurements is essential, but exact knowledge of the undisturbed plasma EDF is not very important or the results of the measurements can be correctly interpreted. That is the case, for example, for the method of plasma electron spectroscopy (PLES) [2, 4], which may be useful for characterization of plasma-chemical processes in the plasma. The PLES method is based on the measurements of nonlocal energetic electrons, arising in a plasma from various volumetric plasma-chemical processes, in an afterglow or afterglow-like plasma with low-electron temperature (typically of the order of 0.1 eV) [9, 10]. Measurements of the high-energy portion of the EES (usually in the energy range between 1 and 20 eV) can provide analytical information about the gas mixture.

In this paper, we demonstrate experimentally that using the wall probe can accurately measure micro-discharge plasma EES for interpreting plasma-boundary interactions and plasma-chemical reactions in atmospheric-pressure plasma with a nonlocal energetic-electron energy spectrum. For nonlocal plasmas, the EES at the boundary is also representative of the entire plasma.

2. Probe theory at high-pressure plasma

A probe accurately measures the EDF of electrons within one energy relaxation length (λ_ε) from the probe. Note that for elastic collisions this relaxation length may be much greater than the mean free path (λ) since elastic collisions within the plasma will preserve electron kinetic energy. Within λ_ε, the total electron energy is not spatially dependent, and the EDF is considered nonlocal [5]. If electrons are further away from the probe (greater than λ_ε) the recorded electron total energies are now spatially dependent, and the EDF is considered local. The probe size must also be taken into consideration, as a probe larger than λ_ε would detect different electron energies depending on the location on the probe. For a cylindrical probe the radius (R) determines the probe size. These parameters, λ_ε, λ, and R determine how the probe measurements should be interpreted [3]. For a low pressure plasma, where $R << \lambda$, the Druyvesteyn formula is valid and the EDF is proportional to the second derivative of the probe current with respect to the probe potential. For a high pressure plasma, where $R >> \lambda$ but $R << \lambda_\varepsilon$, the EDF is proportional to the first derivative of the probe current [1–4].

The wall probe in this work is relatively large compared to the plasma volume surface. The transport of electrons to the probe is diffusive and therefore, as mentioned above, the first derivative will be used to determine the EES. Thus, in our experiments, shown below, the measured first derivative of the probe current with respect to the applied probe potential is the experimentally recorded. The EES accurately indicates signature of plasma-chemical reactions in the plasma, but their relative ratio of secondary peaks may not correspond to the exact ratio as the undisturbed EDF in plasma. If it is necessary, for example, for determination of the undisturbed EDF, this could be corrected for by calibrating with known gas mixtures or numerical modeling so that accurate ratios can be determined. Note, that the presence of a specific target gas component can be monitored in a gas mixture from the measured EES without correction.

Thus, if λ_ε is substantially greater than the plasma volume size, the EES can be measured by the wall probe for the entire volume. For noble gases and atmospheric pressure that corresponds to the plasma volume size of order of 100 µm. If λ_ε is comparable or somewhat smaller than the plasma volume size, high-energy peaks at the EES still can be measured, but can be accompanied by additional background electron continuous spectrum due to partial energy relaxation of energetic electrons. Note, that adding air to Helium can reduce λ_ε and provide the transition from nonlocal to local regime without alternation of the discharge volume or gas pressure.

3. Experimental devices

For the experiments, several micro-plasma short dc discharge devices were created. They were fabricated with three layers of molybdenum metal foils with thickness of 100 µm separated by two sheets of mica insulation with thickness of 110 µm. The different devices have holes with the diameter from 65 µm to 450 µm, which formed cylindrical discharge cavities that passed through the entire five layers. The holes were produced by drilling with a bit for the diameters greater than or equal to 200 µm. In the devices with the holes of less than 200 µm, the holes were produced with a laser. In all

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devices, the inner molybdenum layer formed a wall probe, while the outer layers of molybdenum served as the hollow cathode and anode. The discharge was open to air with a flow of Helium gas. The pictures in figure 1 represent three different devices and plasma conditions.

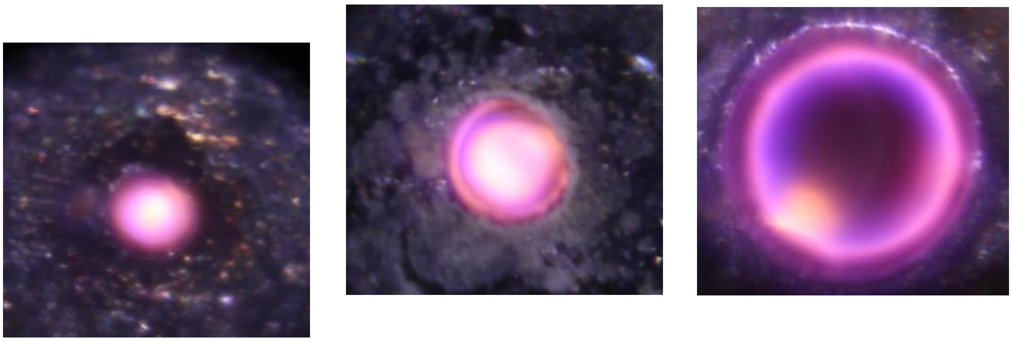

Figure 1. Pictures of the devices with the laser produced hole with the diameter of 100 μm (left) and the drill-bit produced hole with the diameter of 200 μm (middle) and 450 μm (right).

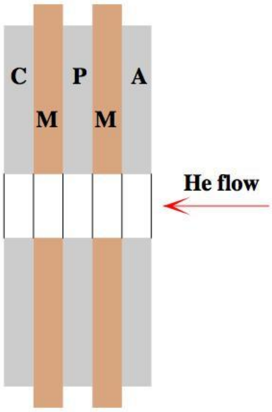

Figure 2. A sketch of discharge device. Hollow-cathode (C), hollow-anode (A), wall probe (P) and mica wall (M).

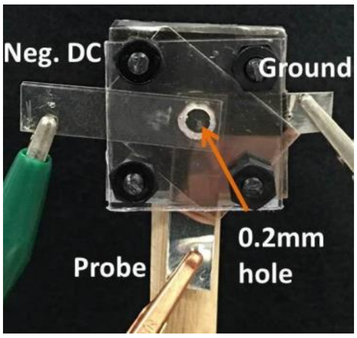

Figure 3. A picture of the experimental device with the hole of the diameter of 200 μm.

For the device with the 450 μm hole, the plasma is not uniform and confined to the edge of the hole. This is considered to be a local plasma. At 200 μm, the plasma is more uniform but still exhibits some non-uniformities (λ_ε is about the discharge radius). At 100 μm and lower, the plasma is practically uniform and is assumed to be nonlocal. A sketch of the device is shown in figure 2 and a picture is shown in figure 3. EES measurements were taken with devices at 200 um and lower. It is expected that each dc device will exhibit an afterglow-like plasma, where the majority of electrons have a Maxwellian EDF with very low temperature, T_e, of the order of 0.1 eV. In this plasma, electrons with energies between 1 and 20 eV are created due to volumetric plasma-chemical reactions.

4. **Results of the experiments and discussion**

Typical results of measurements of wall probe current j_w and its first derivative with respect to probe potential dj_w/dV are shown in figures 4 and 5 (I_d is the discharge current). It is found that the wall probe I–V trace is sensitive to the presence of energetic electrons created due to presence in the plasma of Helium metastable atoms. The first derivative of the probe current with respect to the probe potential shows peaks revealing energetic electrons at specific energies arising due to plasma chemical reactions (see figure 5). The maximums at 15 and 20 eV correspond to binary collision between He metastable atoms (Penning ionization) or de-excitation of metastable atoms by slow electrons.

Maximum about 3–5 eV corresponds to Penning ionization of Nitrogen molecules by metastable Helium atoms. The energy of created electrons depends on the condition of the Nitrogen molecule and the type of metastable atom. Groups of electrons near energies of 10 eV may correspond to Penning ionization of Oxygen by metastable Helium atoms. The energetic electron peaks at the EES for the discharge with lower diameter are more pronounce which could be connected to increasing ratio between λ_ε and the discharge diameter. That corresponds to transition from regimes with nonlocal EES to regimes with local EES are visible in the discharges, shown in figure 1. It is seen that due to energetic electrons the wall potential can be much higher than that, associated with the ambient electron kinetic energy [11]. The device with smaller plasma diameter has lower wall potential, which is about –10 V in contrast to –29 V, as shown in figure 4.

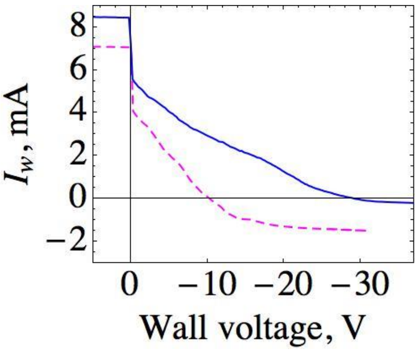

Figure 4. Wall current I_w with respect to wall potential in a Helium dc discharge surrounded by air. Dashed curve (65-µm device, I_d = 6.5 mA) and solid curve (200-µm device, I_d = 8.2 mA).

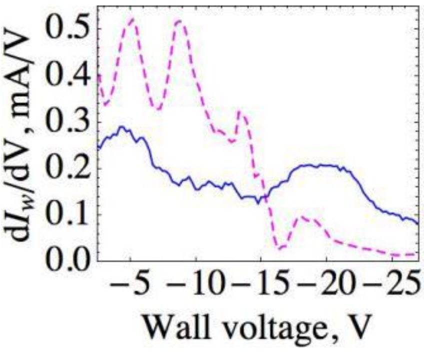

Figure 5. First derivative, dI_w/dV, with respect to wall potential for figure 5. Dashed curve (65-µm device, I_d = 6.5 mA) and solid curve (200-µm device, I_d = 8.2 mA).

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