Electron density measurements and calculations in a helium capacitively-coupled radio-frequency plasma

Z. Donkó[(*)1], B. Z. Bentz[2], P. Hartmann[1], A. Derzsi[1]

[1] *HUN-REN Wigner Research Centre for Physics, Budapest, Hungary*

[2] *Sandia National Laboratories, Albuquerque, NM, USA*

[(*)] *donko.zoltan@wigner.hun-ren.hu*

The electron density is the most fundamental characteristic of various types of plasmas. Nonetheless, a precise measurement, as well as an accurate calculation of this quantity still represent challenges. In low-pressure radio-frequency (RF) discharges, in particular, various types of probes (Langmuir probes, hairpin probes, etc.) can be used for measurements of the electron density. These probes, however, inevitably cause some disturbance in the plasma due to their very presence. Microwave interferometry or laser diagnostics methods provide non-intrusive alternatives for these measurements. Computations of the electron density are also not straightforward, despite the availability of sophisticated numerical approaches and high-performance computational resources [1]. In this work, we report Laser-Collision Induced Fluorescence (LCIF) measurements and numerical modeling calculations of the electron density and the electron temperature in low-pressure capacitively-coupled radio-frequency discharges in helium gas. The experimental plasma source is a symmetric Capacitively Coupled Plasma (CCP) cell, with a pair of stainless-steel electrodes of 14.2 cm diameter, placed at a distance of L = 4 cm from each other. The gas pressure is between 50 mTorr and 200 mTorr and RF peak-to-peak voltages between V_{PP} = 150 V and 350 V are used at a frequency of f = 13.56 MHz.

The LCIF method is an extension of the Laser Induced Fluorescence (LIF) technique [2]. Both LIF and LCIF employ a laser to excite atoms in the plasma from a lower-lying level (L1) to a higher-lying level (L2). In LIF, the radiation emitted from the atoms as these decay spontaneously from the higher-lying level (L2) to a lower-lying level (L3, typically different than the original lower-lying level, L1) can be measured to quantify the density of the atoms in the level L1. In the case of LCIF, in addition to monitoring the LIF signal from the level L2, the emission is also monitored from additional levels, which are close to L2 but have somewhat higher energy. These excited levels are populated via collisions between the laser excited species (L2 level) and energetic electrons.

The numerical simulations are based on a Particle-in-Cell / Monte Carlo Collisions (PIC/MCC) simulation that includes He atoms in several excited levels in addition to the ground-state He atoms, as targets for electron-impact collisions. This way, besides the conventionally considered (direct) electron-impact excitation and ionization processes, stepwise excitation and ionization processes can also be included, as well as electron-impact de-excitation of the atoms in the excited levels, and ionization caused by collisions between excited (typically metastable) atoms. The density of the He atoms in the various excited levels is computed in a Diffusion-Reaction-Radiation (DRR) module that solves the diffusion equations of the He atoms in the excited levels, considering their sources and losses, which includes the rates of the electron-impact processes (obtained in the PIC/MCC module) as well as the rates of the radiative channels between the various levels, and quenching processes [3]. We consider 18 excited levels of He atoms, with electron-impact cross sections taken from [4] and include 37 strong radiative transitions. The PIC/MCC and the DRR modules are executed repeatedly until convergence is reached. The importance of this computational approach lies in the fact that the accumulation of excited atoms in the plasma, even at relatively low pressures, can significantly change the plasma characteristics, like the electron energy distribution function and the electron density [3,5].

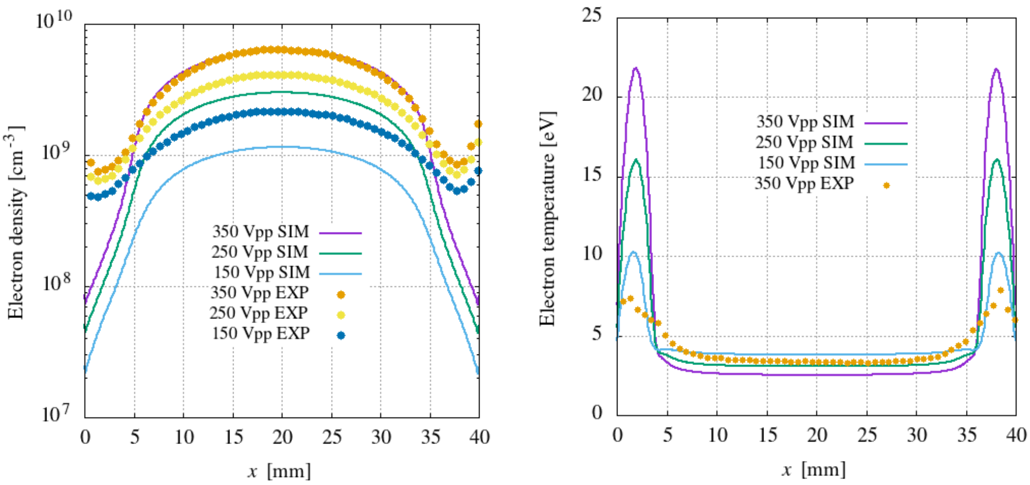

Fig. 1: The spatial distribution of the electron density (a) and electron temperature (b) in the He CCP at 200 mTorr gas pressure, as obtained from the experiments ("EXP") and the numerical calculations ("SIM") at the various excitation voltages.

The results of the measurements and the calculations are compared in Fig. 1. for the case of 200 mTorr He pressure. The best agreement between the data for the electron density (see panel (a)) is obtained at the highest driving voltage of V_{PP} = 350 V, the agreement gets worse with decreasing V_{PP}, but remains within a factor of two, which is acceptable considering the experimental errors as well as the accuracy of the input data of the discharge model. A general feature of the measured electron density distributions is the relatively high density in the sheath regions, which needs further clarification. The electron temperature values in the plasma bulk agree very well as it can be seen in Fig. 1(b). The measurement, however, appears to underestimate T_e in the sheath regions. Ongoing experimental studies target scanning the discharge characteristics over an extended domain of operating conditions (RF voltage and gas pressure).

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