Topic number: 6

Modelling of a filamentary rf discharge at atmospheric pressure

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The discharge filaments as occurring in a miniaturized non-thermal atmospheric pressure plasma jet (ntAPPJ) have been investigated by a self-consistent fluid model. The ntAPPJ is configured as a capacitively coupled capillary jet discharge which is illustrated in Fig. 1. Argon gas flows between the outer and the inner quartz capillary in the indicated direction with flow rates between 0.1 and 2 slm. A precursor mixture flows through the inner capillary, gets activated in the outlet and feeds the thin film deposition on the substrate. Two ring-shaped electrodes are attached to the outer capillary. Standing or rotating discharge filaments are observed between the upper electrode, driven by an rf voltage at 27.12 MHz, and the lower grounded electrode. One single or multiple filaments occur depending on the applied power and flow rate. Extensive experimental investigations have been performed [1] to analyse the discharge behaviour and the transition between different so-called locked and stationary modes. As an example, stationary filaments are shown in Fig. 2.

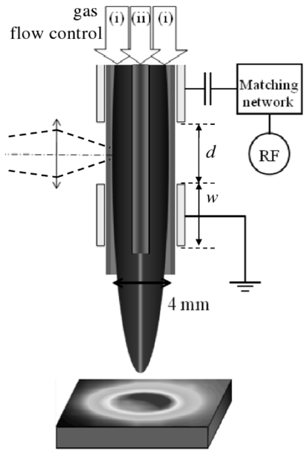

Fig. 1: Setup of ntAPPJ.

In the framework of the fluid model a single stationary filament driven by the rf voltage is considered. A simplified two-dimensional geometry is used which is axisymmetric with respect to the axis of the filament as shown in Fig. 3. The filament has the length of 5 mm and is assumed to be confined by an outer dielectric surface E at the radius $R = 0.2$ mm. Dielectrics are attached on both sides of the filament as well. They represent the wall of the outer quartz capillary. The rf voltage is applied at the outer surface A of the dielectric and the outer surface B is grounded. The influence of the gas flow on the filament is neglected in this approach. Furthermore, the gas temperature is assumed to be constant at 300 K.

The model includes electrons, atomic and molecular argon ions as well as argon atoms excited in metastable, resonance and higher levels. The set of equations comprises continuity equations for these species, Poisson's equation, the electron energy balance and balance equations for the charges on the surfaces C, D and E between the dielectrics and the plasma. Secondary electron emission with $\gamma = 0.1$ is included at C and D and recombination of charge carriers is used as boundary condition at C, D and E. The fluxes are taken in drift-diffusion approximation. The electron transport and rate coefficients have been prepared as functions of the mean energy and ionization degree by solving the 0D electron Boltzmann equation including electron-electron interaction.

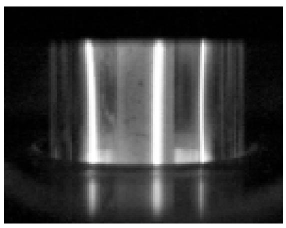

Fig. 2: Stationary filaments observed in the ntAPPJ.

Modelling results at an rf voltage amplitude of 6 kV are shown in Figs. 4 and 5. The figures show only the transition region from the dielectric surface at $x = 0$ to $x = 0.5$ mm, where the filament becomes axially homogeneous. Figures 4a and b illustrate the transition from the more flat radial profile of the electron density near the dielectric towards the profile in the column, which is established due to ambipolar diffusion in radial direction. The

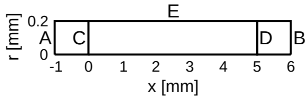

Fig. 3: Simplified geometry for the filament.

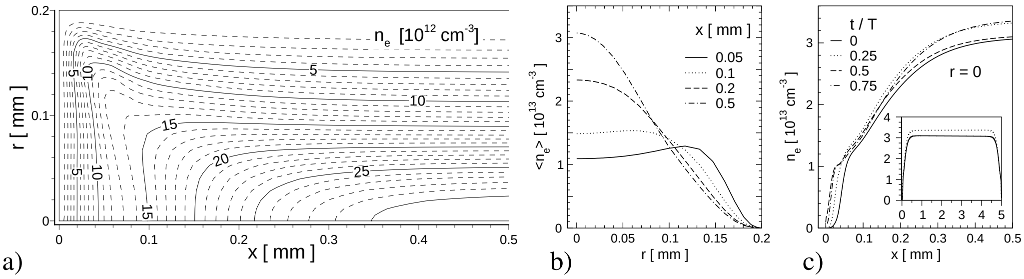

Fig. 4: Period-averaged density (a, b) and modulation of the axial density profile (c) of electrons.

period-averaged electron density reaches a value of about $3{\cdot}10^{13}$ cm^{-3} in the centre. Fig. 4c shows the axial profile of the electron density $n_e(x, r = 0, t)$ in the sheath and transition region and its modulation during one period. The sheath with strongly oscillating space charge has a width of about 0.05 mm. The modulation of the electron density in the column amounts to about 10%.

The period-averaged axial density profiles of electrons, ions and the sum of excited atoms at $r = 0$ are shown in Fig. 5a. The molecular ions represent the dominant positive charge carrier due to the large rate coefficient of the reaction $Ar^{+}+2Ar \rightarrow Ar_2^{+}+Ar$. A pronounced peak of the densities of excited atoms and atomic ions is found in the sheath. It is caused by the increase of the electron mean energy up to about 7 eV in this region during the cathode phase. The molecular ions exhibit a more smooth density profile due to their diffusion.

Figure 5b presents the period-averaged power gain of the electrons, which is about 80% of the total power supplied to the plasma. Large values can be observed in the sheath with a flat structure and a local maximum at about $r = 1.6$ mm. The power gain is low in the transition region from $x \approx 0.05$ to 0.3 mm where both the electric field and the electron density have lower values. The total period-averaged power supplied to the electrons in the filament amounts to about 0.38 W. The contributions of the axially homogeneous column ranging from $x = 0.5$ to 4.5 mm and both sheaths with a width of 0.05 mm to the total power amount to about 80% and 5.7%, respectively. The maxima of the current density are about 0.95 A/cm^2 in the column, which is far beyond the value where the transition from the α to the γ mode is expected [2].

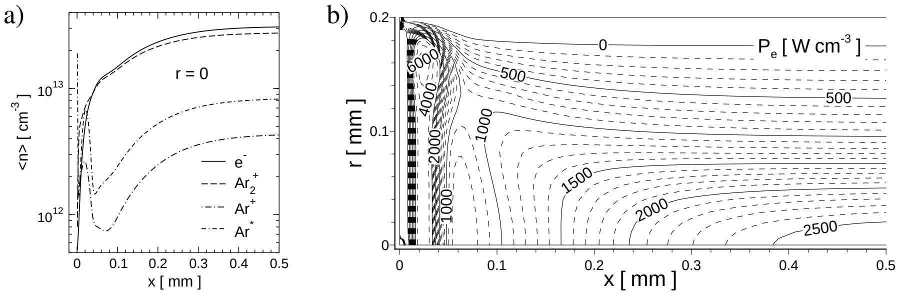

Fig. 5: Period-averaged axial density profiles of charge carriers and excited atoms at $r = 0$ (a) and period-averaged electron power gain (b).

The study represents a first approach to describe the filaments occurring in the ntAPPJ in stationary mode. Further improvements as the transition to higher power and the inclusion of additional processes leading to the constriction may lead to larger electron densities which were estimated from spectroscopic measurements in locked mode to be of the order of 10^{14} cm^{-3}.

Acknowledgment
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References

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[2] N. Balcon, G. J. M. Hagelaar, J. P. Boeuf, 2008, IEEE Trans. Plasma Sci., 36, 2782