Simulation of helium discharge dynamics in thin dielectric tubes at atmospheric pressure and discharge interaction with tube surface

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This paper presents numerical simulations of the discharge propagation in thin dielectric tubes with two rings (driven and grounded) wrapped around the tube in helium at atmospheric pressure for a positive constant applied voltage. The current peak of 0.11 mA occurs when the discharge crosses the gap between the electrodes. The Joule heating released in the discharge in 300 ns is 20.6 μJ which corresponds to an average increase of temperature of 0.25 K. The deposition of surface charge is also shown and it is interesting to note that after saturation the amount of negative charges is twice higher than the amount of positive surface charges.

Since a few years, atmospheric pressure plasma microjets formed by pulsed helium discharges ignited in thin dielectric tubes have received considerable interest due to their potential for biomedical applications. High-speed photographs have demonstrated that jets are composed of discrete plasma bullets travelling with velocities in the range $10^6 - 10^8\,\mathrm{cm/s}$ in ambient air [1]. So far, most experiments have been dedicated to the study of the plasma plume. Recently, to better understand the ignition and dynamics of plasma jets, experiments have been done to study the discharge inside tubes [2]. We therefore propose to simulate the discharge dynamics in tubes as in Ref. [3] but we introduce more complex chemistry and study more in detail the discharge current and the discharge-surface interaction.

The studied set-up consists of a dielectric tube with an internal radius and a thickness of 1.6 mm as in Ref. [3]. High voltage and grounded rings are wrapped around the tube and separated by 1 cm. Both rings are 0.5 cm wide. In this work, we have considered a constant applied voltage of 12 kV. To ensure that the potential decreases down to zero far from the set-up, grounded planes are placed at 10 cm from left and right edges of the driven ring.

A 2D fluid model is used to simulate the discharge propagation in the tube: continuity equations for charged species are coupled to Poisson equation using cylindrical coordinates. The helium chemistry scheme is taken from [4]. Photoionization is added based on [5]. Ionization coefficient is taken from [6] and other transport coefficients and reaction rates dependent on local field are taken from [7]. On the dielectric interface, we consider secondary emission due positive ion impact ($\gamma = 0.1$). Discharge current is calculated based on volume integral of power density and divided by the applied voltage:

$$I = \frac{1}{U_\mathrm{a}} \int_V \vec{J} \cdot \vec{E}\, \mathrm{d}V \,, \tag{1}$$

where V is the volume of the computational domain. In this work we also define a current due to Joule heating, calculated using in Eq. (1) the conductive current density $\vec{j}$ instead of the total current density $\vec{J}$.

Fig. 1 shows the discharge current and current due to Joule heating. The discharge current reaches its maximum of 0.11 A in about 30 ns. Then the discharge current decreases by two orders of magnitude in the following 100 ns. The total energy inputted from power source to the discharge in 300 ns is then 41.0 μJ. The current due to Joule heating is increasing as the total current when the discharge propagates in the gap between rings but lately become smaller. The Joule heating in 300 ns is then 20.6 μJ. If we assume that all Joule heating is transfered immediately to homogeneous heating of helium neutral gas inside and between rings (with $c_\mathrm{V} = 3.12\,\mathrm{kJ/(kg\,K)}$) it corresponds to an increase of temperature of 0.25 K.

In the studied configuration the discharge is ignited in the tube close to the outer edges of the driven ring and then propagates on both sides ($x > 5.5$ cm and $x < 5$ cm) as 2 positive discharge fronts (electric field directed in same direction as discharge propagation) [3]. Fig. 1 shows the electric field on the axis of symmetry and surface charge density on tube interface for 3 different times. At $t = 30\,\text{ns}$ the discharge crosses the gap between rings and this corresponds to the peak value of the current. We note that the deposition of negative surface charges inside the driven ring is already high. Then at 50 ns the discharge propagates behind the grounded ring ($x < 3.5\,\text{cm}$), negative charge still increases and positive surface charge just starts to be deposited inside the grounded ring. The discharge continues its propagation at the time 300 ns (not stopped yet) even if the current in the discharge has decreased to values in the range 0.001 mA and the electric field in the channel is reduced to values $0.01 - 0.1\,\text{kV/cm}$. The positive surface charge inside the grounded ring is saturated at this time and it is interesting to note that the amount is approximatively half of the amount of the negative surface charge inside the driven ring.

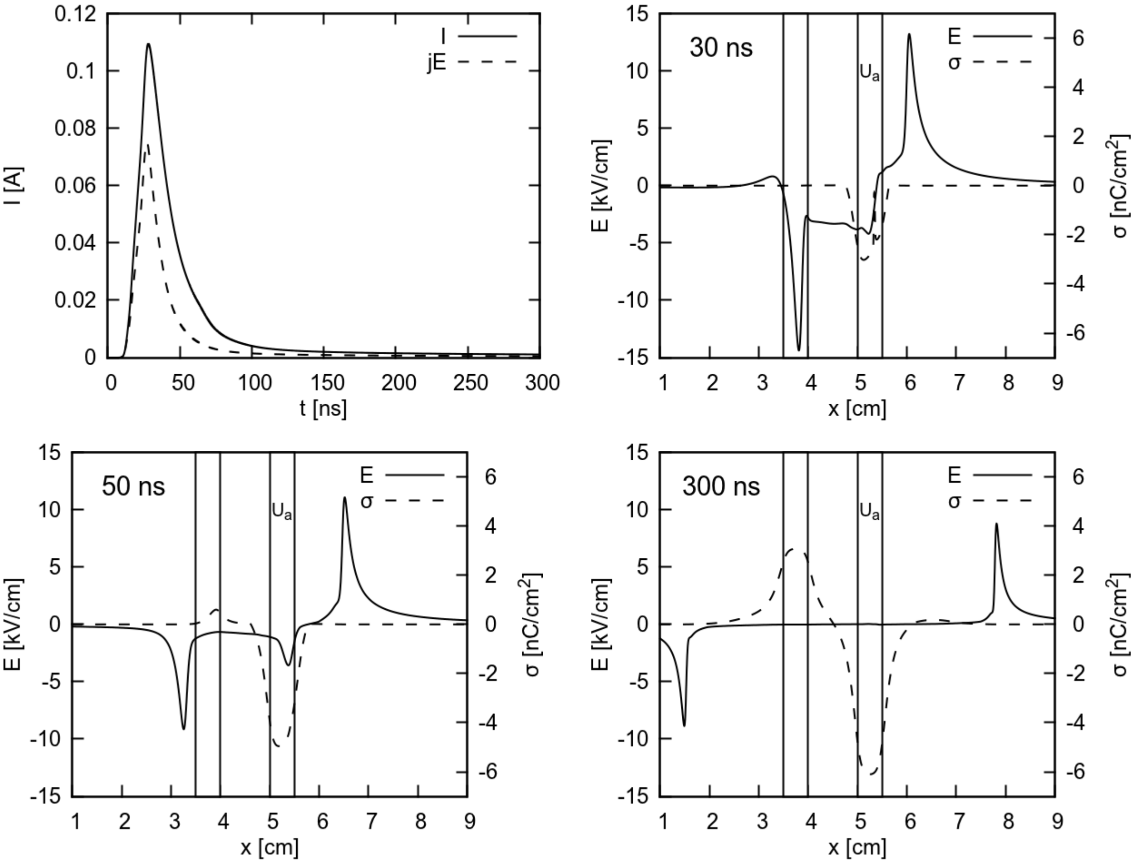

Fig. 1: The discharge current and current due to Joule heating are shown on left top figure. Other figures show the electric field on axis of symmetry and surface charge density on tube interface for times $t = 30$, 50 and 300 ns. The grounded ring is shown as rectangle with label U$_\text{a}$ between 5 and 5.5 cm. $U_\text{a} = 12\,\text{kV}$.

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References

[1] M. Teschke, J. Kedzierski, E. G. Finantu-Dinu, D. Korzec, and J. Engemann, *IEEE Trans. Plasma Sci.* **33** (2005) 310.

[2] Q. T. Algwari and D. OConnell, *Appl. Phys. Lett.* **99** (2011) 121501.

[3] J. Jansky, A. Bourdon, *Appl. Phys. Lett.* **99** (2011) 161504.

[4] G. Naidis, *J. Phys. D: Appl. Phys.* **44** (2011) 215203.

[5] G. Naidis, *J. Phys. D: Appl. Phys.* **43** (2010) 402001.

[6] D. Maric, M. Radmilovic-Radenovic, and Z. L. Petrovic, *Eur. Phys. J. D* **35** (2005) 313.

[7] G. J. M. Hagelaar and L. C. Pitchford, *Plasma Sources Sci. Technol.* **14** (2005) 722.