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Influence of Elementary Processes on Form of Apokampic Discharge

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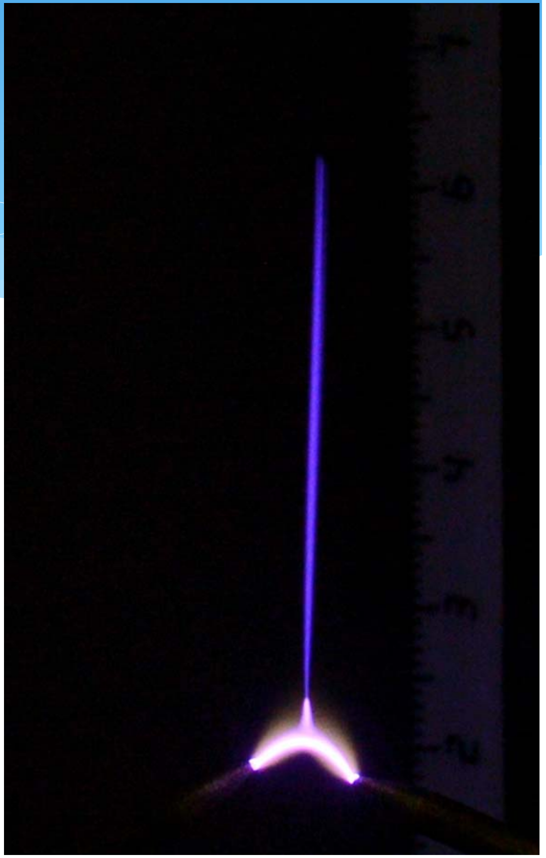
Abstract

Results of modeling an apokampic discharge at atmospheric pressure in an oxygen medium with various rates of elementary processes, such as dissociation of oxygen molecules by electron impact and electron attachment, are presented. It is shown that reduction of the electron attachment rate leads to increasing of the jet propagation velocity, and a decrease in the rate of direct dissociation greatly increases the diameter of the apokampic jet.

INTRODUCTION

The apokampic discharge at atmospheric pressure was first experimentally detected in 2016 [1]. The discharge peculiarity is that it looks like a luminous elongated jet propagating perpendicular to the bended discharge channel. The main discharge channel is formed between two needle electrodes inclined to each other.

Therefore, this discharge type was termed apokampic, or apokamp (in Greek: από – from, καμπη – bend). In the framework of the previous model [2, 3], we demonstrate the propagation mechanism and the structure of the apokampic jet.



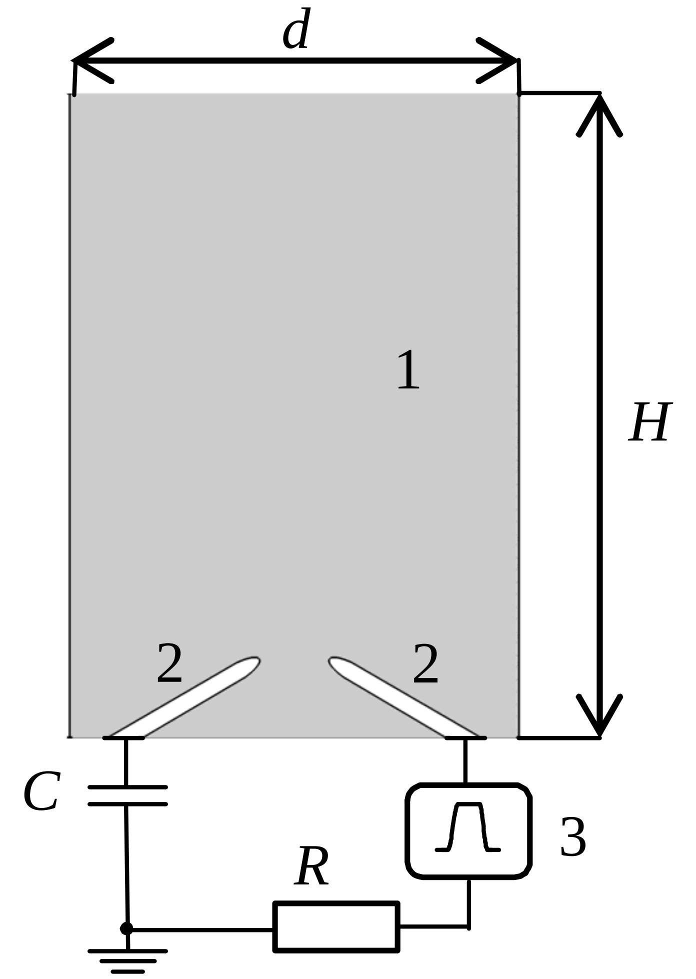
[1] E.A. Sosnin, V.A. Panarin, V.S. Skakun, E.K. Baksh and V.F. Tarasenko “Dynamics of apokamp-type atmospheric pressure plasma jets,” *EPJ D*, vol. 71, no. 2, art. 25, 2017.
[2] V. Kozhevnikov et al. “Apokamp-type gas discharge phenomenon: Experimental and theoretical backgrounds,” *EPL*, vol. 129, art. 15002, 2020.
[3] E.A. Sosnin, V.A. Panarin, V.S. Skakun, et al. ”Apokampic discharge: formation conditions and mechanisms,” *Russian Physics Journal*, vol. 62, p. 1289, 2019.

THEORETICAL MODEL
the main simplifications

The needle electrodes *2* used in the experiment are replaced by flat endless electrodes. The chosen geometry made it possible to take into account the nonaxisymmetric propagation of the plasma jet, and, at the same time, apply two-dimensional modeling to accelerate the calculation time.

Blade electrodes with a curvature of 0.1 mm were located at an angle of 120 degrees to each other. The electrodes are placed in an endless discharge chamber with a width of *d* = 50 mm and a height of *H* = 70 mm. The distance between the electrodes was 8 mm.

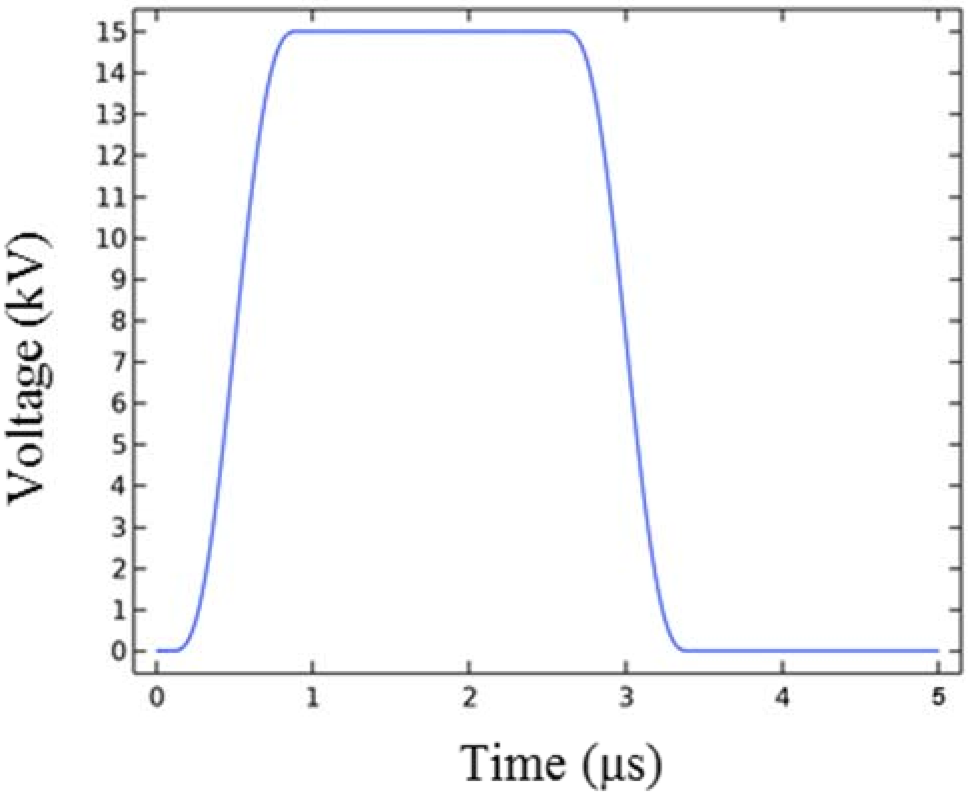
One electrode was at a floating potential and connected to the ground through the capacitance *C* = 3 pF.



THEORETICAL MODEL
the main simplifications

A trapezoidal pulse with a duration of 3 μs and an amplitude of 15 kV was applied to another electrode through a ballast load R = 10 kΩ.

For the background plasma, the initial electron number density was n_{eo} = 10^6 cm^{-3}, and initial average energy was equal to 0.025 eV.



Time profile of high-voltage pulse

THEORETICAL MODEL
the main simplifications

The simulation was based on a non-stationary drift-diffusion macroscopic model [4] using the finite element method on a triangular grid in the Plasma module of the COMSOL Multiphysics 5.2a code.

The experiments suggest that an apokamp forms at the positive polarity of the high-voltage pulse. For this reason, we had to include the description of photoionization processes into the model, since it is in principle impossible to characterize the streamer propagation from the positive high-voltage electrode. This process of the seed-electron generation in a gas volume was calculated on the basis of a model reported in [A. Bourdon, V. P. Pasko, N. Y. Liu, *et al*. "Efficient models for photoionization produced by non-thermal gas discharges in air based on radiative transfer and the Helmholtz equations," *Plasma Sources Sci. Technol.*, vol. 16, pp. 656–678, 2007].

The main reactions for the oxygen medium

The calculations were carried out for various reaction rates.
Initially, reaction rates were taken from reference [1-3] (here T_e in eV):

1) ionization by electron impact with the formation of an O_2^+ ion

$e + O_2 \Rightarrow 2e + O_2^+$, $9\cdot10^{-10} T_e^2 \exp(-12.6/T_e)$ [cm³/s]

2) **attachment of electrons** with the formation of an O_2^- ion;

$e + 2O_2 \Rightarrow O_2 + O_2^-$, $2\cdot10^{-29} (0.03/T_e)$ [cm⁶/s]

3) **direct molecule dissociation** with the formation of atomic oxygen;

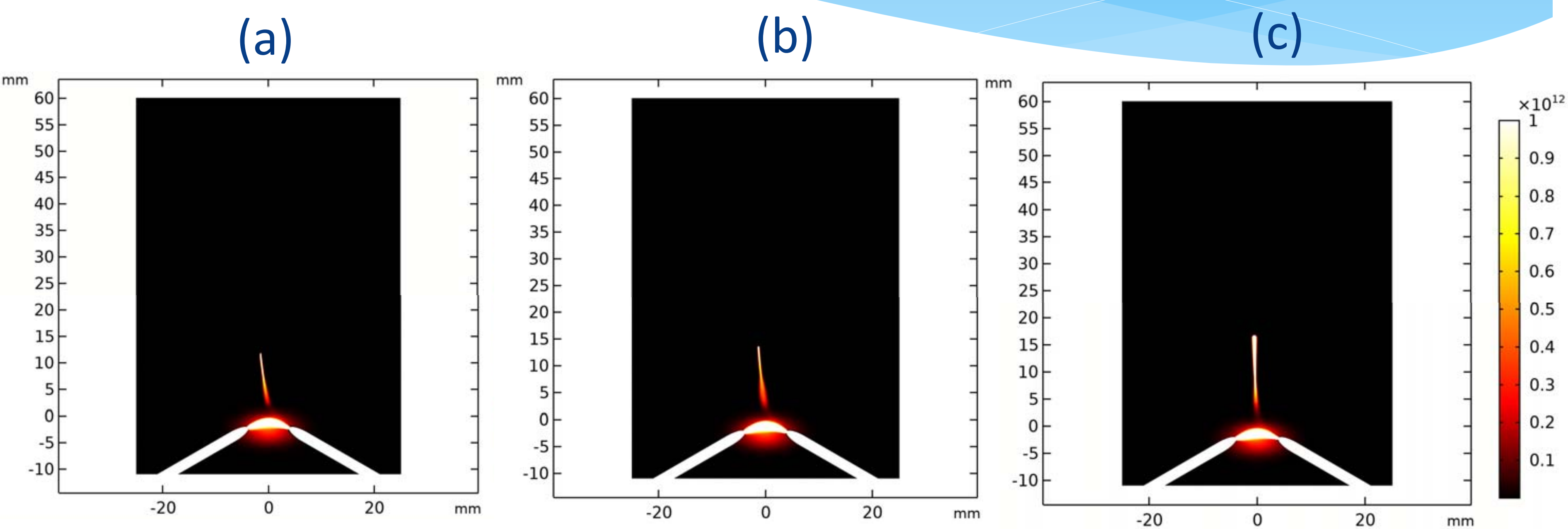
$e + O_2 \Rightarrow e + 2O$, $4.2\cdot10^{-9} \exp(-5.6/T_e)$ [cm³/s]

4) **ion-ion recombination**

$O_2^+ + O_2^- + O_2 \Rightarrow 3O_2$, $2\cdot10^{-25}$ [cm⁶/s]

[1] I.A. Kossyi et al., *Plasma Sources Sci. Technol.*, vol. 1, pp. 207–220, 1992.
[2] J. He, Y. T. Zhang, *Plasma Process. Polym.*, vol. 9, pp. 919–928, 2012.
[3] M. A. Lieberman, A. J. Lichtenberg, Principle of Plasma Discharges and Materials Processing, New York: Wiley, 2005.

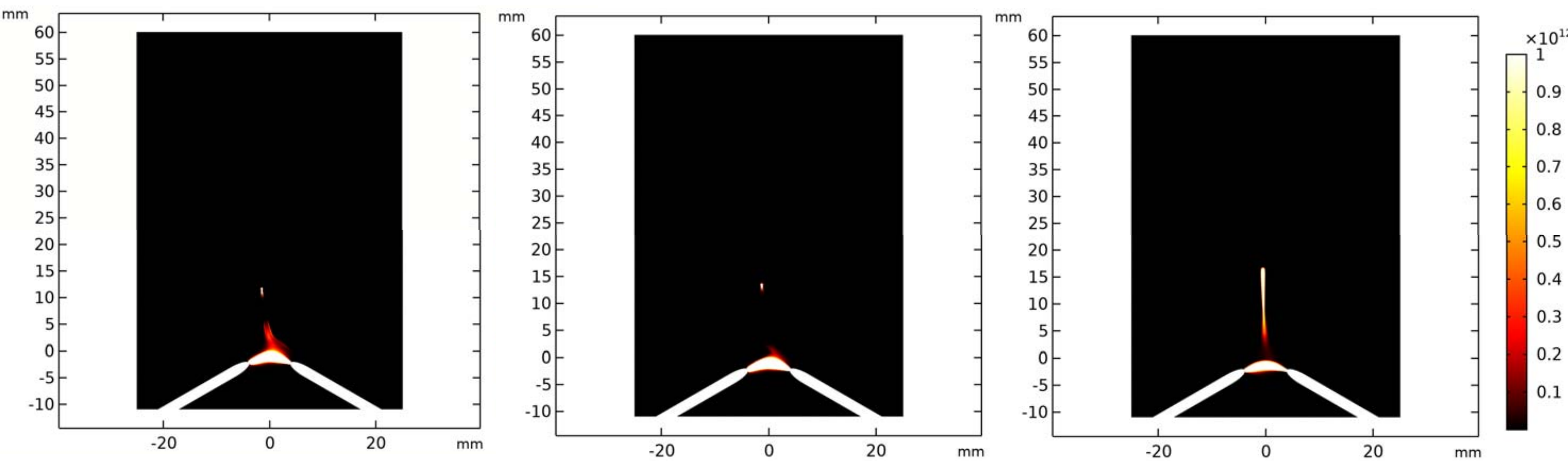
Spatial distribution of the O_2^+ number density (cm^{-3}) for the 1 μs time point from the beginning of the pulse supply



(a) Rates for the reactions 2) and 3) were taken from the literature data.
(b) The only molecules dissociation rate has been reduced by 100 times of magnitude.
(c) The only electron attachment rate has been reduced by 100 times of magnitude.

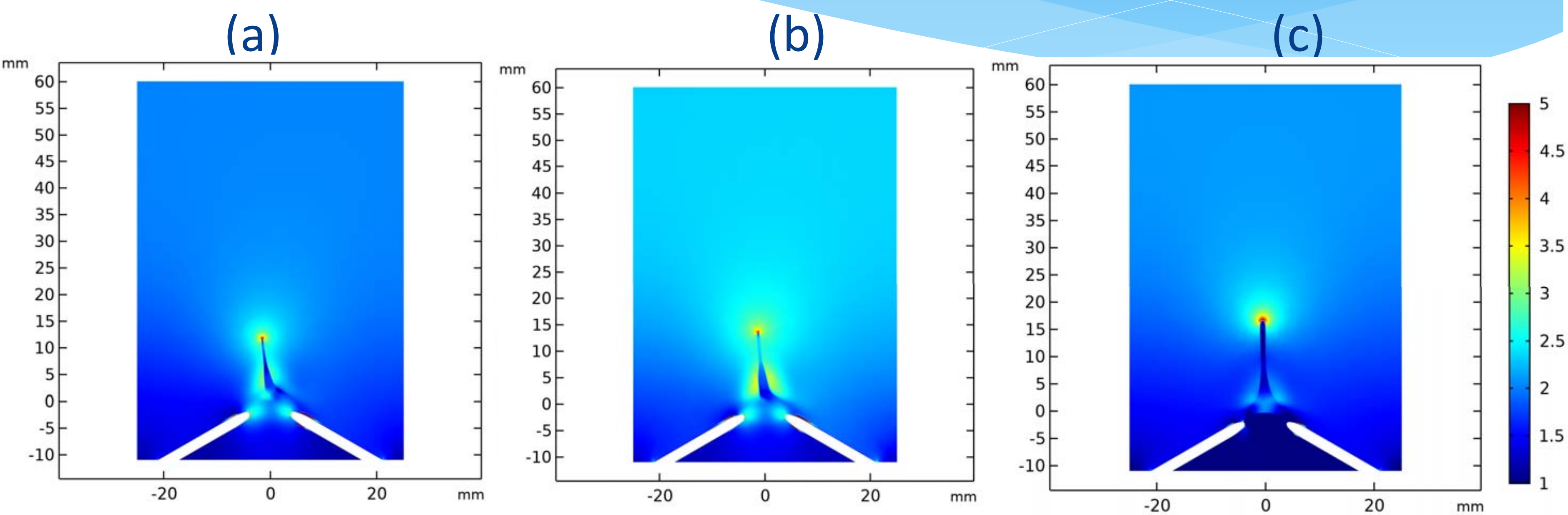
Spatial distribution of the electron number density (cm^{-3}) for the 1 μs time point at the different rate of elementary processes

(a) (b) (c)



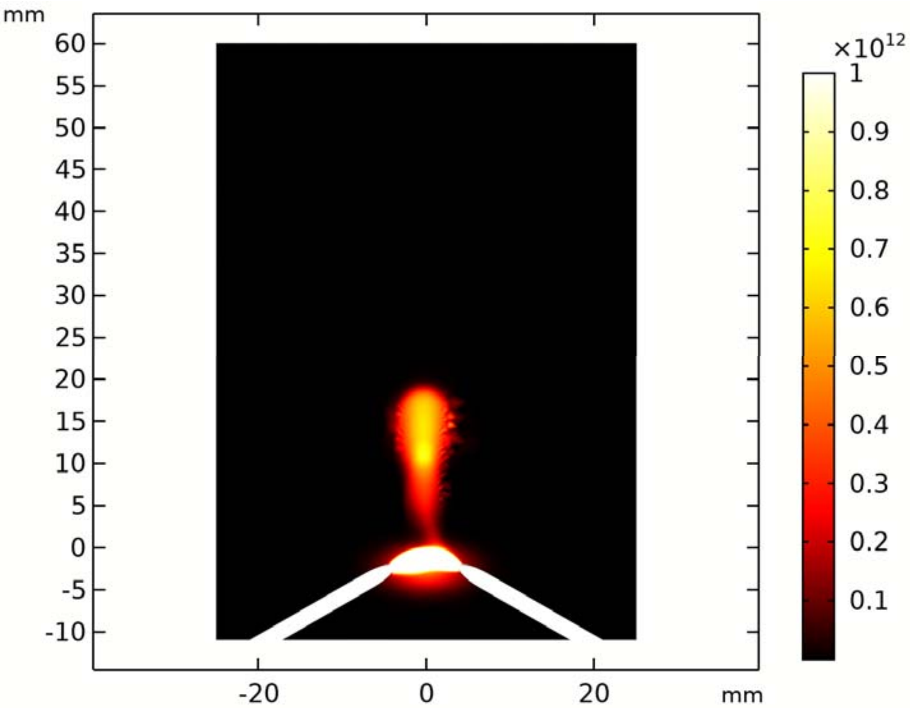
(a) Rates for the reactions 2) and 3) were taken from the literature data.
(b) The only molecules dissociation rate has been reduced by 100 times of magnitude.
(c) The only electron attachment rate has been reduced by 100 times of magnitude.

Spatial distribution of the mean electron energy (eV) for the 1 μs time point at the different rate of elementary processes

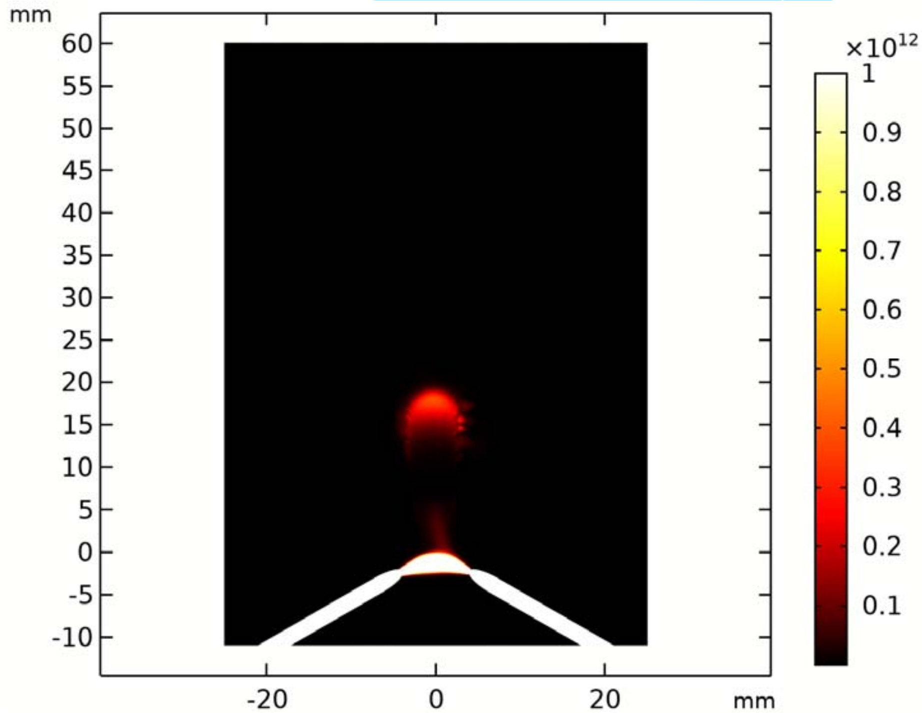


(a) Rates for the reactions 2) and 3) on slide 7 were taken from the literature data.
(b) The only molecules dissociation rate has been reduced by 100 times of magnitude.
(c) The only electron attachment rate has been reduced by 100 times of magnitude.

Spatial distribution of the O_2^+ number density (cm^{-3}) (a) and free electron number density (cm^{-3}) (b) for the time point of 0.65 μs without direct dissociation collisions



O_2^+



e

What does dissociation rate affect?

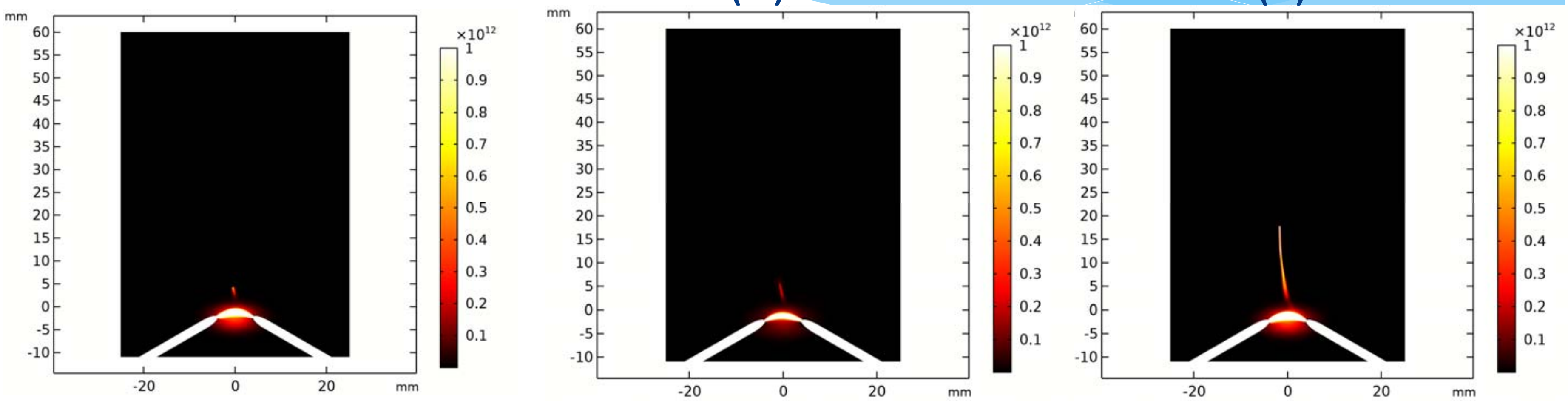
- Suppression of the direct dissociation rate by 100 times slightly increases the propagation velocity of jet and noticeably heats the electrons especially on the side surface of the jet. At first glance, the influence of the dissociation rate can be considered weak.
- The typical simulation result of the apokamp in "atomic electronegative gas" are shown in slide 11. In this gas, there is no significant decrease in the mean electron energy due to low threshold energy dissociation reaction. Therefore, the jet spreads and loses stability already at early stage of jet development. As a result, a thin and narrow jet cannot form at all.

How does the electron attachment?

* Comparing the (a) and (c) images in slide 8,9 and 10, we can see some results. A 100-fold decrease in the attachment constant strongly changes the parameters of the growing jet. The diameter of apokampic jet increases by several times and its shape becomes almost symmetrical with respect to the main channel and electrodes. The velocity of the plasma jet increases too.
* The plasma throughout the entire length of the jet becomes electron-ionic (with normal attachment constant the plasma was ion-ionic). This is evidenced by almost identical images of the spatial distribution of positive ions and free electrons. Thus, the effect of gas electronegativity on apokamp parameters must be recognized as significant.

Spatial distribution of the O_2^+ number density (cm^{-3}) (the rates for all reactions were taken from the literature data) Different pulse amplitude

(a) (b) (c)

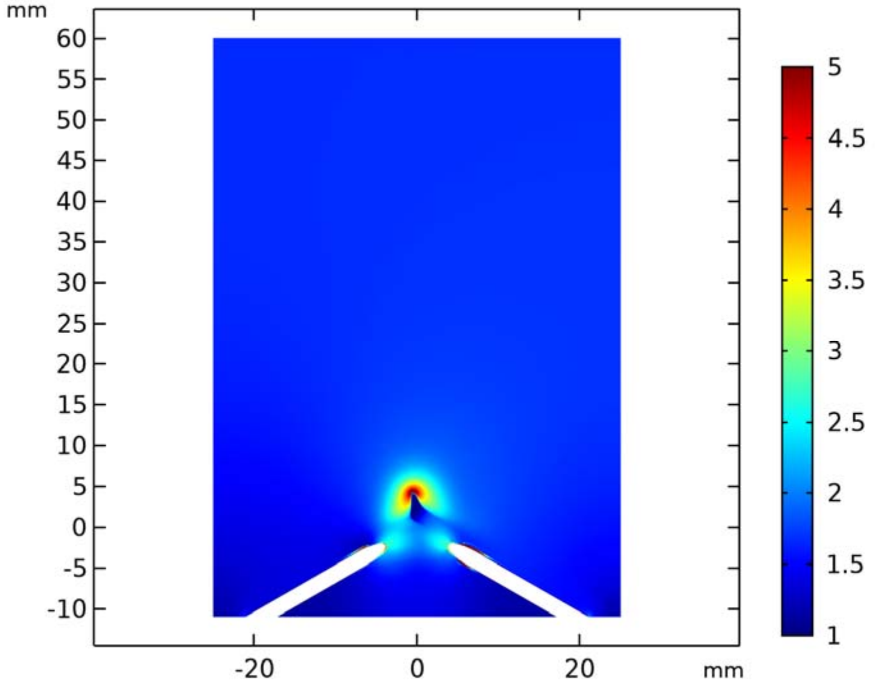


(a) At the voltage amplitude 10 kV for the time point of 1 μs.
(b) At the voltage amplitude 10 kV for the time point of 3 μs.
(c) At the voltage amplitude 20 kV for the time point of 1 μs.

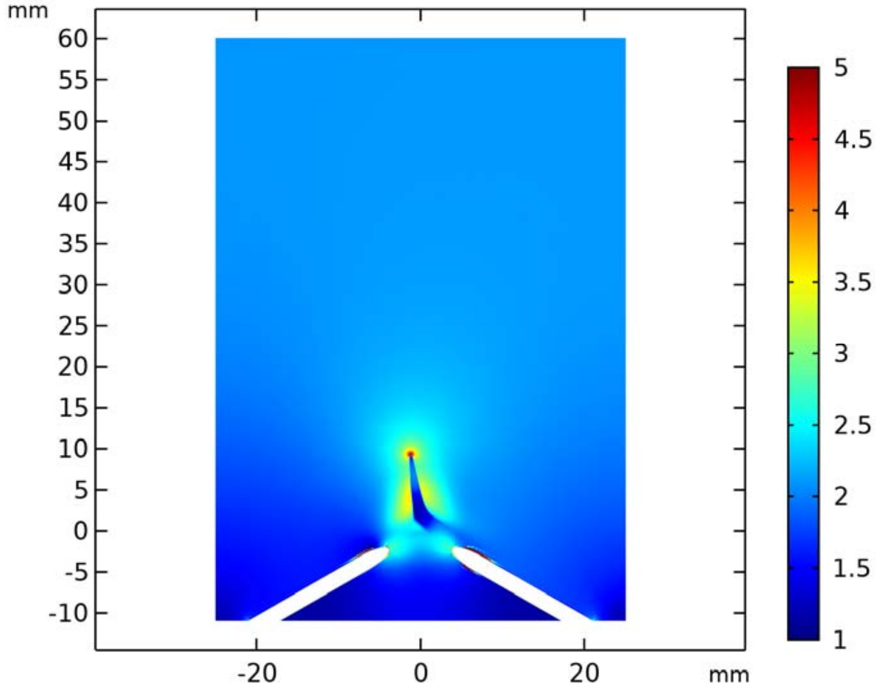
The channel length significantly increases with an increase in the voltage amplitude from 10 to 20 kV. At an amplitude of 10 kV, the apokamp is still developing, but its length does not exceed 8 mm even by the end of the pulse at a time point of 3 μs.

Spatial distribution of the mean electron energy (eV) for the 1 μs time point (the rates for all reactions were taken from the literature data) Different pulse amplitude

10 kV



20 kV



The channel head is less diffuse at the higher voltage amplitude

CONCLUSION

* Based on the two-dimensional plane model and with an incomplete set of the processes under consideration, it is already possible to trace the main characteristic features of this discharge: the formation of a narrow plasma jet perpendicular to the main channel between the electrodes. The results of simulations shows that elementary processes in plasma significantly affect the shape of the apokampic discharge.
* A decrease in the electron attachment rate can lead to a substantial increase in the conductivity of the jet and the elemental composition of its plasma. Besides, decrease the attachment rate leads to accelerated growth of the jet.
* Even a relatively large decrease in the rate of dissociation (up to 100-fold) does not have a large effect on the parameters of the apokampus. The complete exclusion of the direct dissociation process as a low threshold inelastic process with electrons completely changes the breakdown mechanism, making the growth of the apokampic jet impossible. In numerical simulation, this instability manifests itself in the form of rapidly increasing fragmentation of the jet boundary.
* An analysis of the considered set of elementary processes leads to the conclusion that the formation of an apokampic discharge should be observed primarily in electronegative molecular gases, or for a mixture containing any molecular gas. It was such a pattern that was discovered in experiments: the apokampic jet grows only in the presence of a molecular gas, and most clearly manifests itself if there are electronegative impurities.