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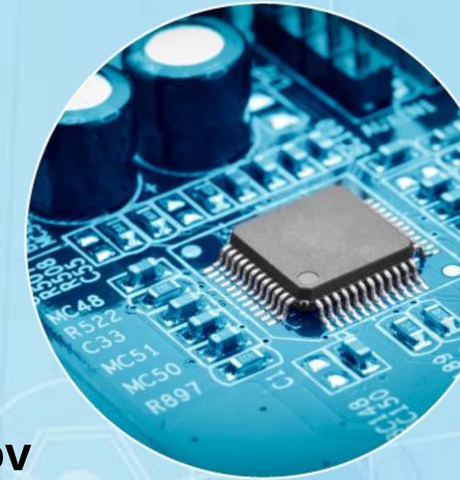

The Numerical Simulation of Apokamp: A Novel Source of an Atmospheric-Pressure Plasma Jet

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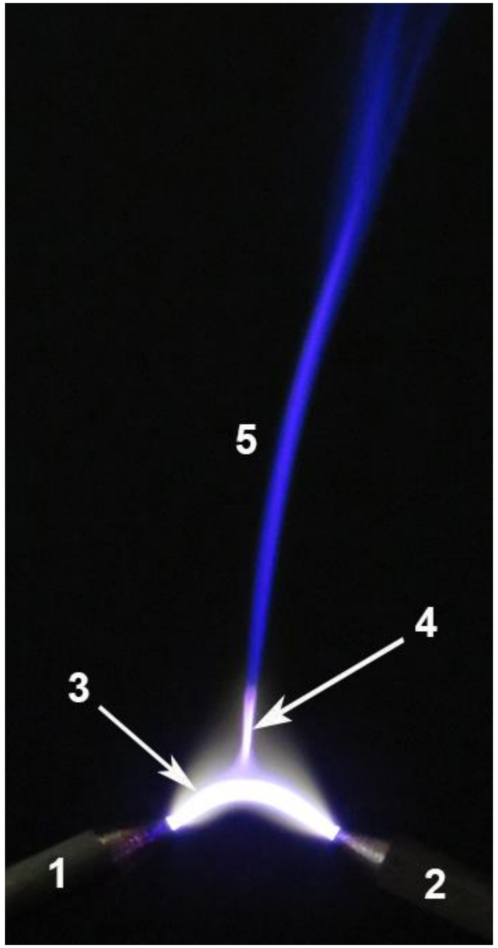
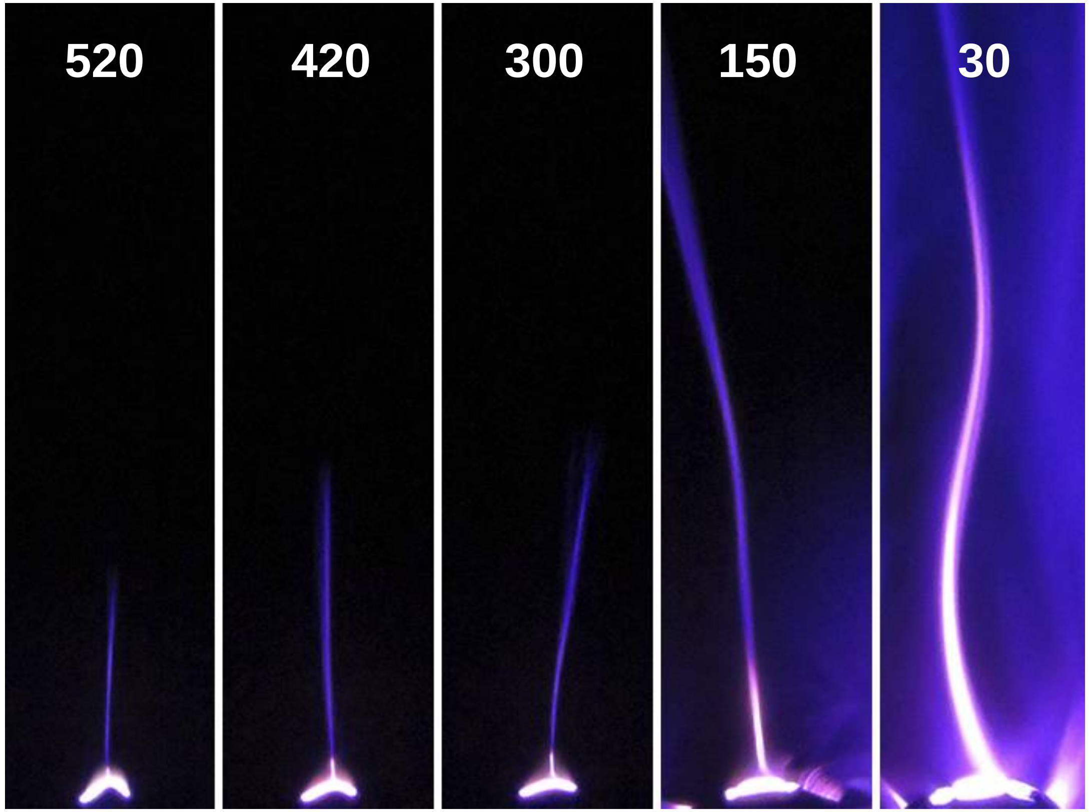
Introduction: experiments*

The phenomenon of “apokampic discharge” or “apokamp” (from Greek ***από*** - “off” and ***καμπη*** - “bend”) was discovered in 2016 at the Institute of High Current Electronics by Eduard Sosnin and his colleagues*.

The phenomenon appearance:

1 – floating potential electrode,
2 – high-voltage electrode,
3 – discharge channel;
4 – bright process;
5 – apokamp channel.



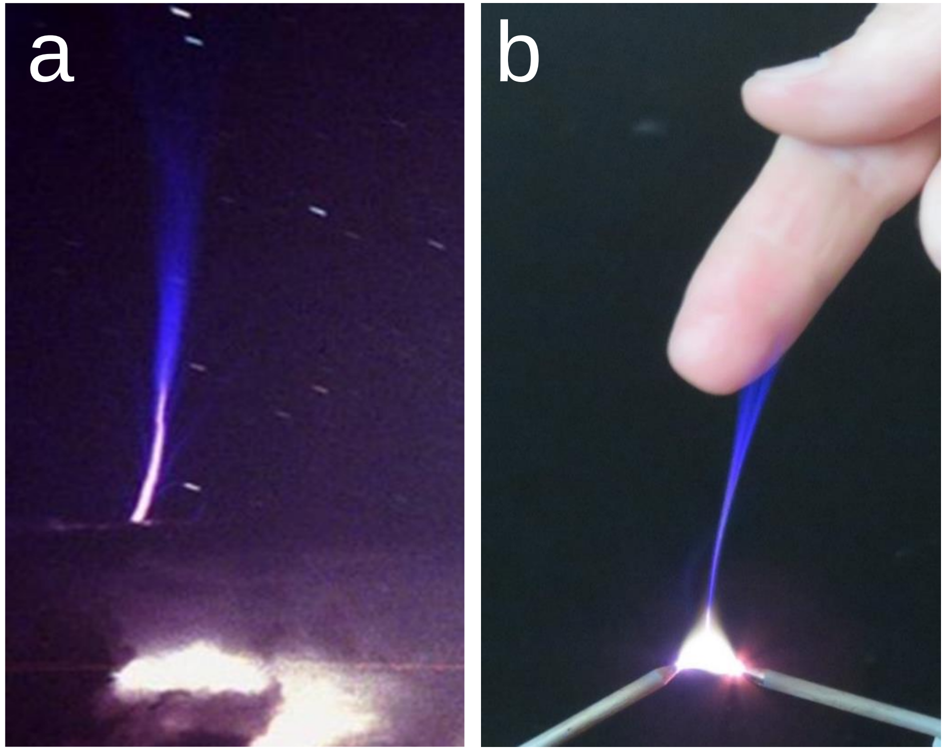


The effect of operating gas (air) pressure change on the shape of apokamp channel (pressure in Torr)

*Sosnin E.A. et al. // JETP Letters, vol. 103, no. 12, pp. 761–764, (2016)
Skakun V.S. et al. // Russian Physics Journal, vol. 59, no. 5, pp. 707–711, (2016)

Experimental details of the apokamp formation

- Apokamp exists only in molecular and electronegative gases or their mixtures (air, O_2, N_2, CO_2, Cl, etc.);
- Apokamp is not caused by any kind natural convection and/or forced gas blowing;
- One of electrodes must have a floating potential (connected to the ground through the small 3-10 pF capacitance), another electrode have to be under pulsed-periodic high voltage potential with low duty cycle ratio (t_{on} ~ 1.5-2.5 μs at 16-50 kHz repetition frequency);
- Both electrodes should be located at some angle to each other (optimal value is 120°);
- One can see on ICCD images that apokamp plasma jet consist of plasma bullets consequence moving with ultrasonic velocities of 100-200 km/s



Similarity between "blue jet" phenomenon (a) and apokamp discharge (b).
Color photograph of a "blue jet" (a) over a large thunderstorm taken north of Reunion Island in the Indian Ocean. The base of the "blue jet" where it can be seen above the top of the clouds is about 18 km altitude and the tip is at 35 km*

*E.M. Wescott et al. // J. Geo. Res.: Space Physics, vol. 106, no. A10, pp. 21549 (2001)

Aims of theoretical simulation in COMSOL Multiphysics

- What causes a pulse-periodic arc discharge to emit fast apokamp jets (directed perpendicular to the main discharge channel)?
- What physical processes make apokamp channel stable regardless convective and temperature instabilities?
- What explains the existence of threshold values of the electrical circuit and the gas pressure parameters at which apokamp emerges and disappears?
- What is the role of the electronegative gas components w.r.t. apokamp formation?
- etc…

“Fluid” model of the discharge plasma dynamics*
(two-moment model equations with local temperature approximation implemented in Plasma Module)

- Electron density & energy density continuity equations

$$\frac{\partial n_e}{\partial t} + \nabla\left[-n_e\mu_e\vec{E} - D_e\nabla n_e\right] = R_i + R_{ph}$$

$$\frac{\partial n_\varepsilon}{\partial t} + \nabla\left[\frac{5}{3}n_\varepsilon\mu_\varepsilon\vec{E} - \frac{5}{3}D_e\nabla n_\varepsilon\right] + \left[-n_e\mu_e\vec{E} - D_e\nabla n_e\right]\cdot\vec{E} = -\Delta\varepsilon R_\varepsilon$$

- Ion density continuity equation

$$\frac{\partial n_i}{\partial t} + \nabla\left[n_i\mu_i\vec{E} - D_i\nabla n_i\right] = R_i + R_{ph} \qquad R_i = \sum_{j=1}^{M} x_j\alpha_j N_n\left|\Gamma_e\right|, \quad R_\varepsilon = \sum_{j=1}^{P} x_j\alpha_j N_n\left|\Gamma_e\right|\Delta\varepsilon_j$$

- Electric field equation (Poisson’s equation)

$$\nabla\vec{E} = \frac{q}{\varepsilon_0}\left(n_i - n_e\right)$$

*Young, F.F., Wu, C.H. // IEEE Trans. on Plas. Sci., 21(3), pp. 312–321 (1993)

Plasma-chemical reactions set (for oxygen)

- Impact ionization ($e + O_2 \Rightarrow 2e + O_2^+$)**
- Impact dissociation ($e + O_2 \Rightarrow e + 2O$)**
- Three-body electron attachment ($e + 2O_2 \Rightarrow O_2 + O_2^-$)*
- Three-body ion-ion recombination ($O_2 + O_2^- + O_2^+ \Rightarrow 3O_2$)*
- Reaction at walls (electrodes) – secondary electron emission with $\gamma = 0.1$
- Photoionization ($h\nu + O_2 \Rightarrow e + O_2^+$)**

$$R_{ph} = \sum_{j=1}^{3} S_j, \quad \Delta S_j - \left[\lambda_j p_{O_2}\right]^2 S_j = -A_j p_{O_2}^2 \left[\frac{0.1 p_q}{p + p_q} R_i\right]$$

$$p_{O_2} = 760\ Torr, \quad p_q = 30\ Torr$$

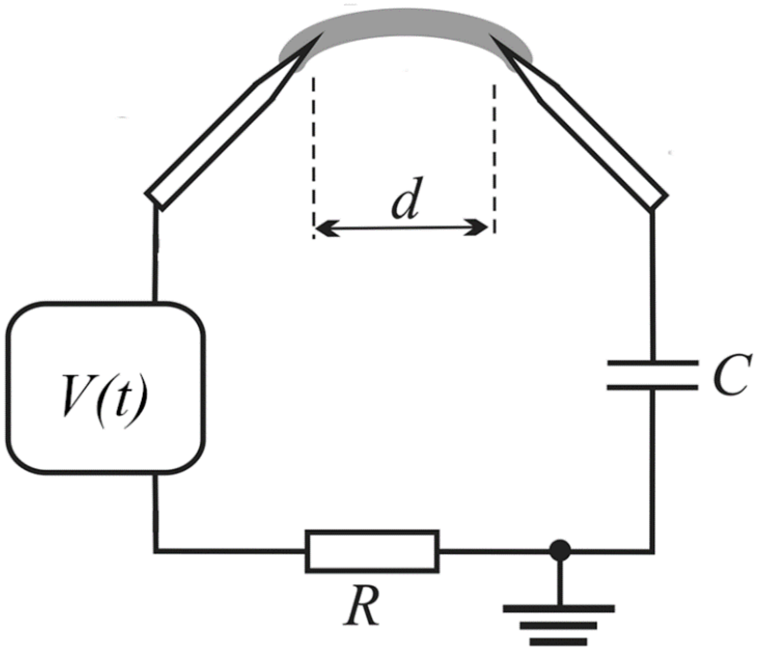
- Other (minor) reactions… could be, but not included!

*Pancheshnyi S. et al. // PRE, 71, 016407 (2005)
**Lee C. & Lieberman M.A. // J. Vac. Sci. Tech. A, 13, 368 (1995)
***Bourdon A. et al. // Plas. Sourc. Sci. Technol., 16, pp. 656-678 (2007)

Additional conditions & numerical method details

- **2D model** instead of 3D experimental configuration
- Non-uniform initial quasi-neutral plasma distribution & temperature profiles were used in order to obtain the effect within one voltage pulse

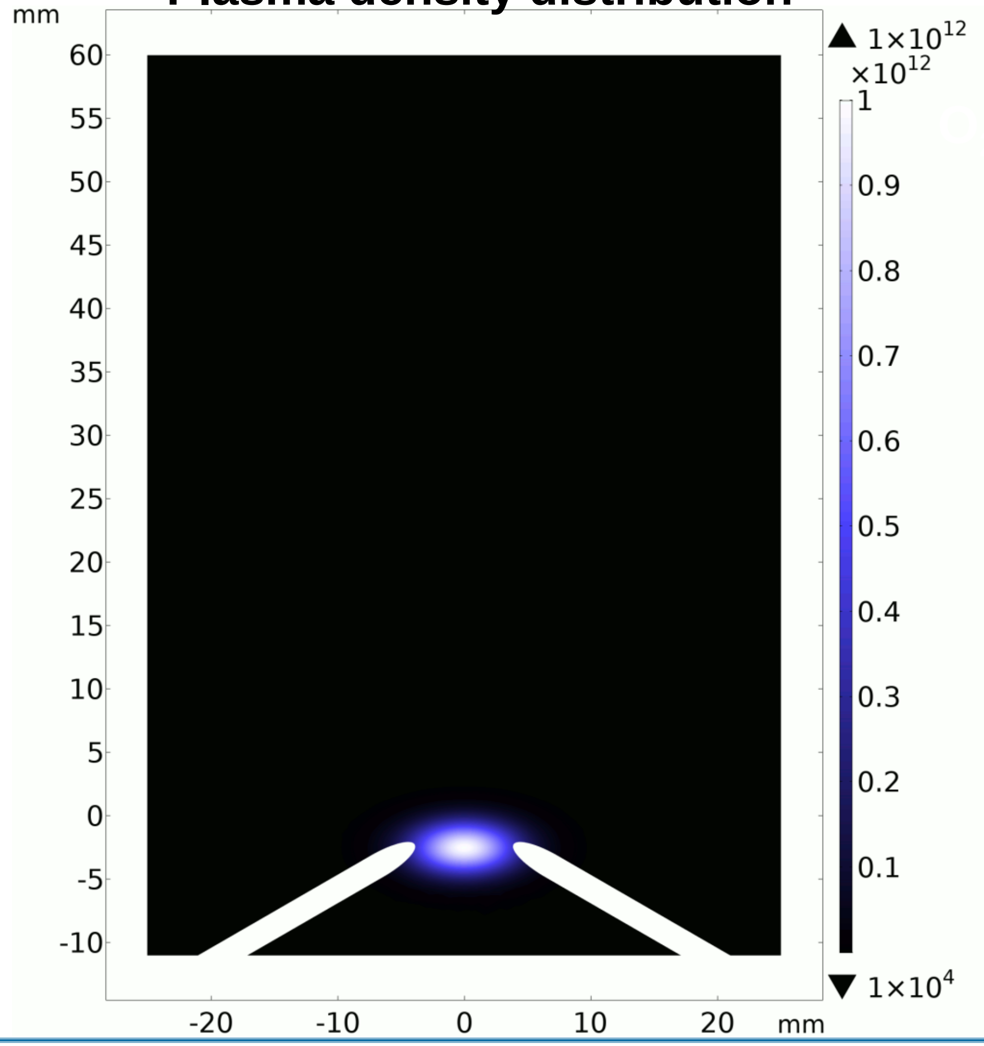
$$\begin{cases} n_i \approx n_e = n_{background} + n_{\max} \exp\left[-\left(\dfrac{x}{\sigma_{n_x}}\right)^2 - \left(\dfrac{y}{\sigma_{n_y}}\right)^2 \right] \\ T = T_{amb} + \left(T_{\max} - T_{amb}\right) \exp\left[-\left(\dfrac{x}{\sigma}\right)^2 - \left(\dfrac{y - y_0}{\sigma}\right)^2 \right] \end{cases}$$



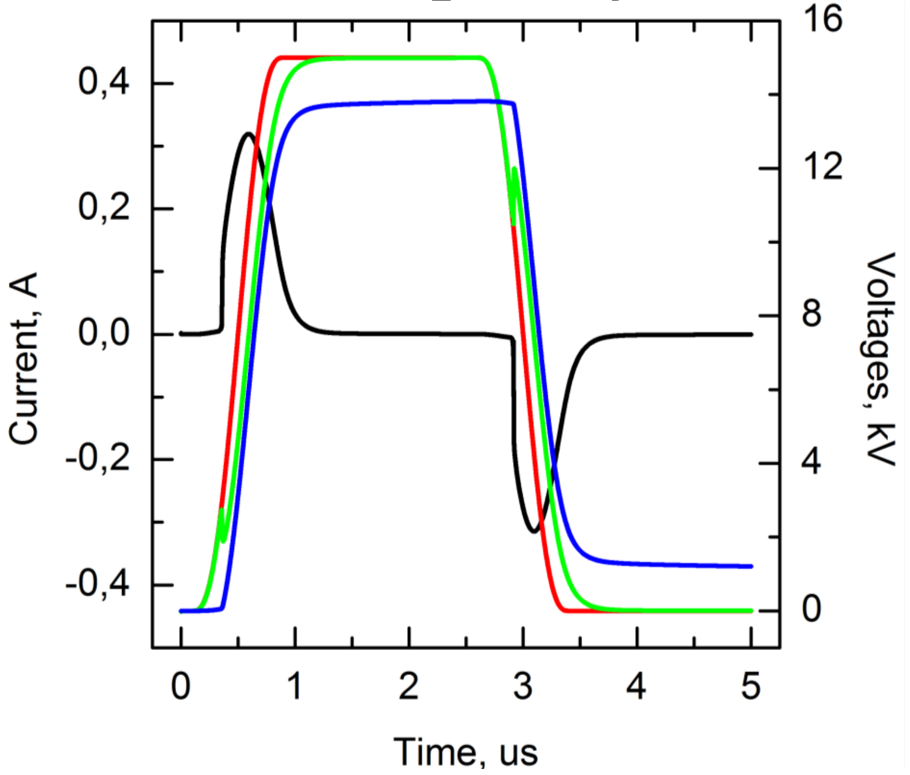
- Plasma module + AC/DC Electrical Circuit module (175000 elements & 1.5 million DOF);
- Boundary fluxes were smoothed for the Helmholtz (photoionization) & the Poisson (electrostatics) equations;
- Reaction terms stabilization have been used avoiding electron density approach values near zero;

Simulation results (per single voltage pulse*)

Plasma density distribution



Current/Voltage time profiles



Problem:

Main discharge channel (arc) parameters and shape are simulated well, **but there's no transversal plasma jet (apokamp)!**

***C = 3.3 pF, R = 10 kOhm, U_{max} = 15 kV, t_{pulse} = 2.5 us**

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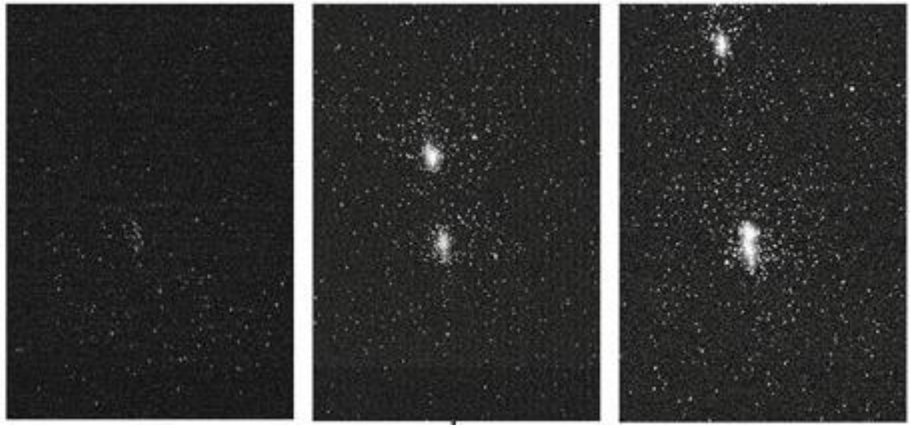
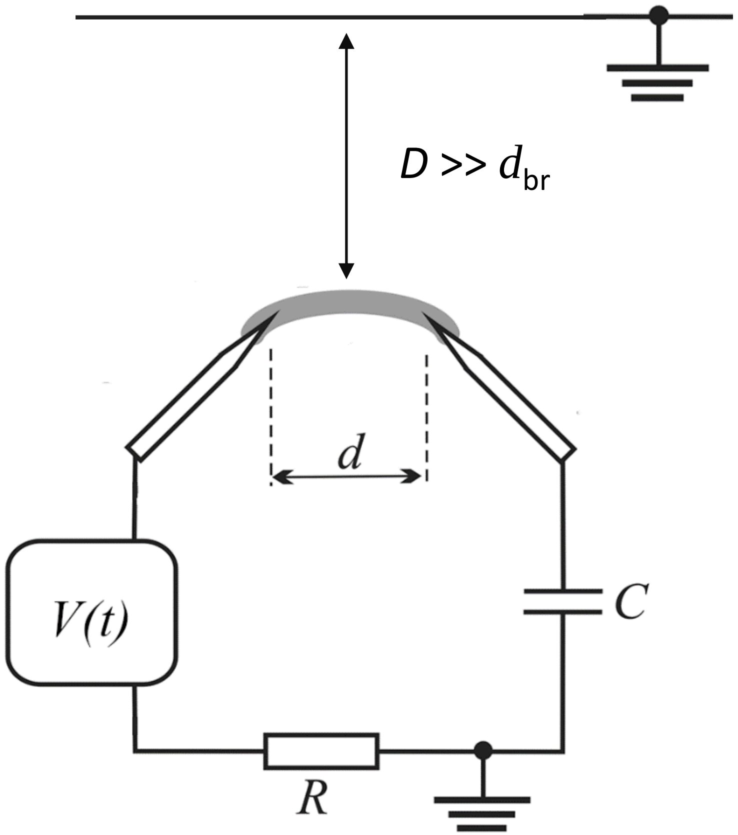
What causes the apokamp jet growth?

Experiments* convincingly show that apokamp has a discrete structure. It is constituted of plasma bullets (plumes) consequence moving with ultrasonic velocities of 100-200 km/s (and even more)!





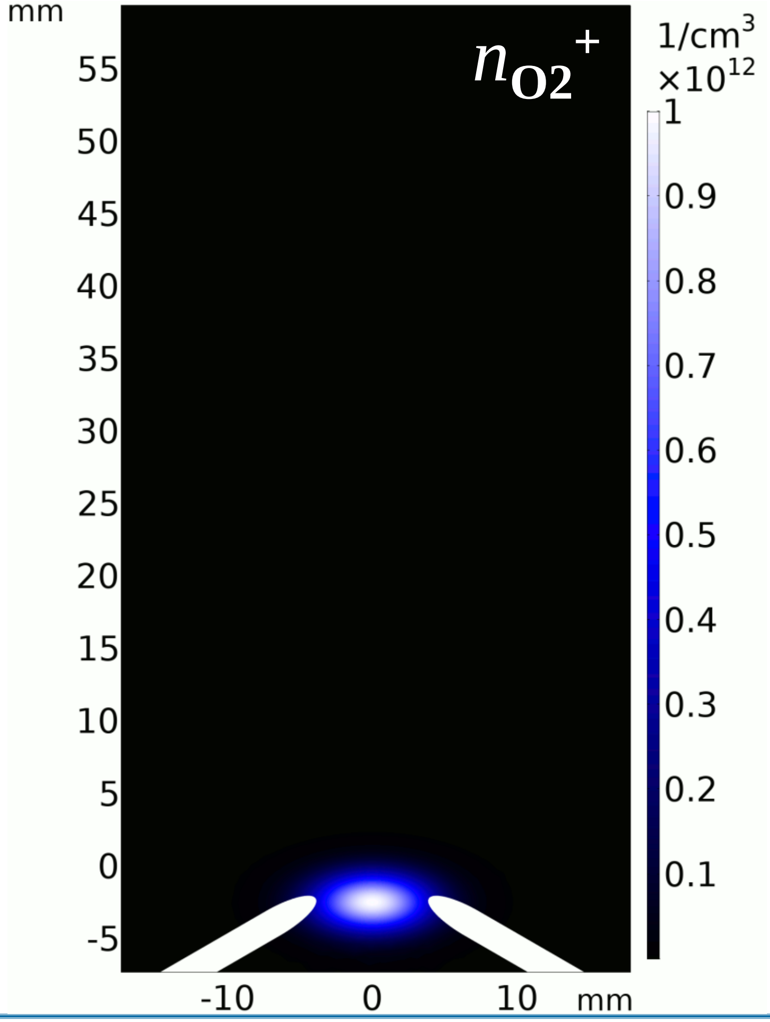
Guess: apokamp may have a streamer-like nature, i.e. pointing out to the existence of weak electric field in the transversal direction to the discharge channel.

What to do: In order to simulate that, we add the third grounded-plane electrode above the main discharge (arc) so the maximum voltage drop between arc and third electrode was 5-10 times lower than static breakdown.

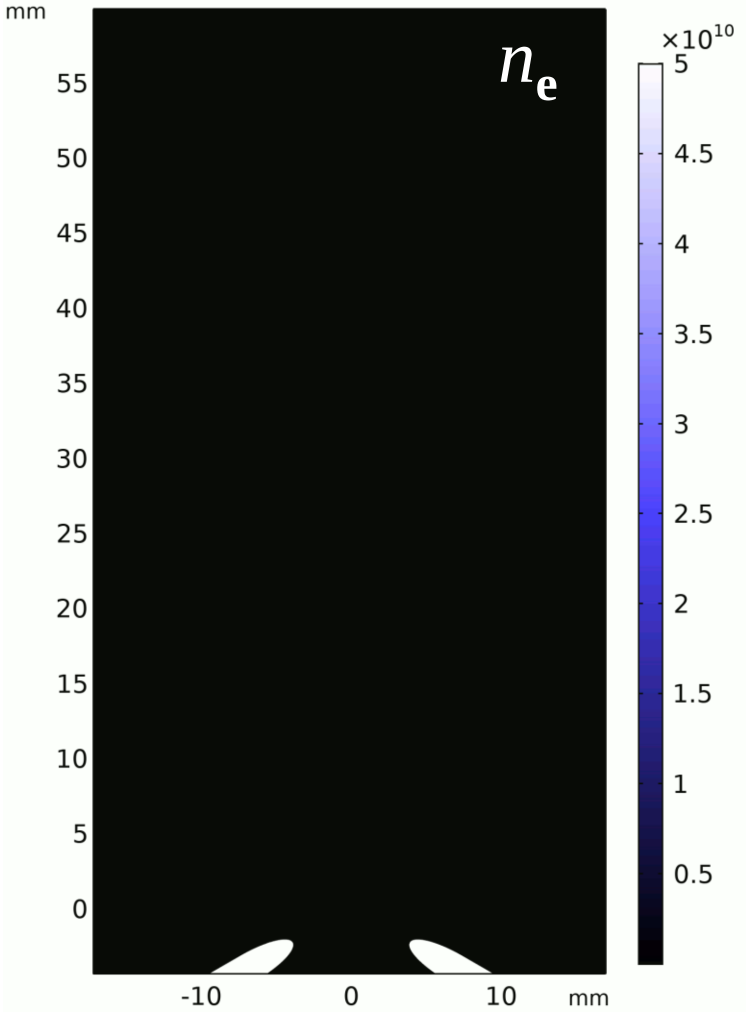
***Sosnin, E.A. // Eur. Phys. J. D, 71, (2017)**

Simulation results (per single voltage pulse, first 1.6 us)

Ion plasma (O_2^+) density distribution



Electron density distribution (plumes)

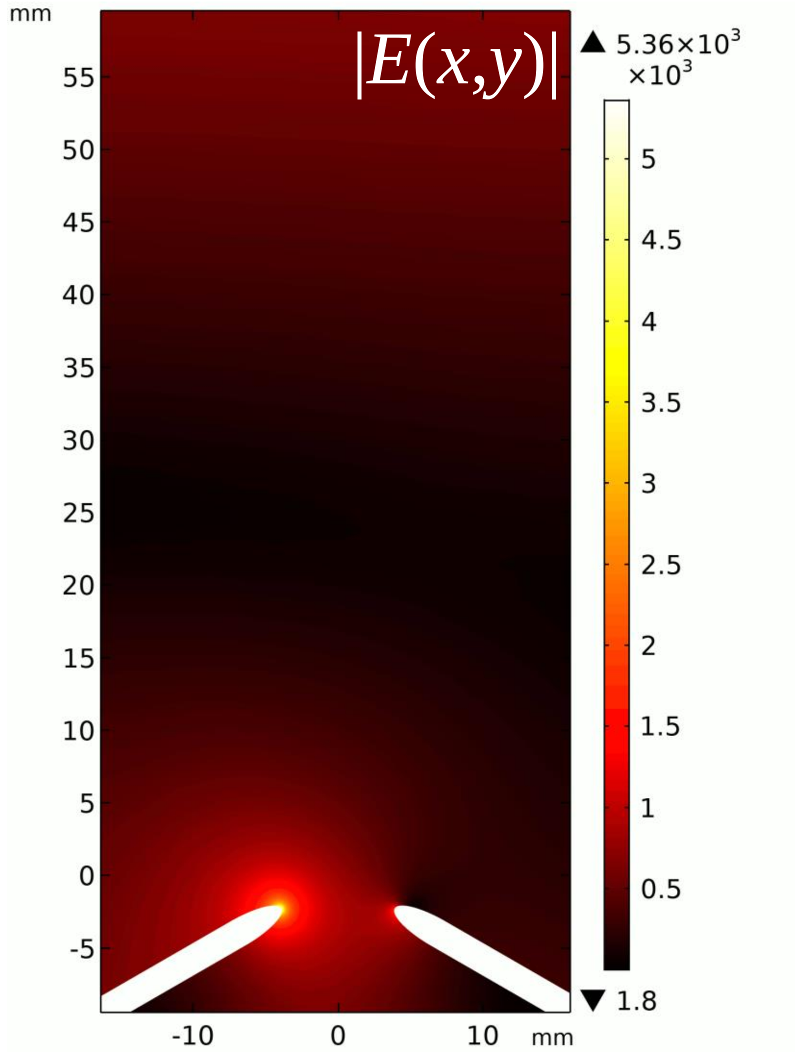


Electric field evolution (first 1.6 us)

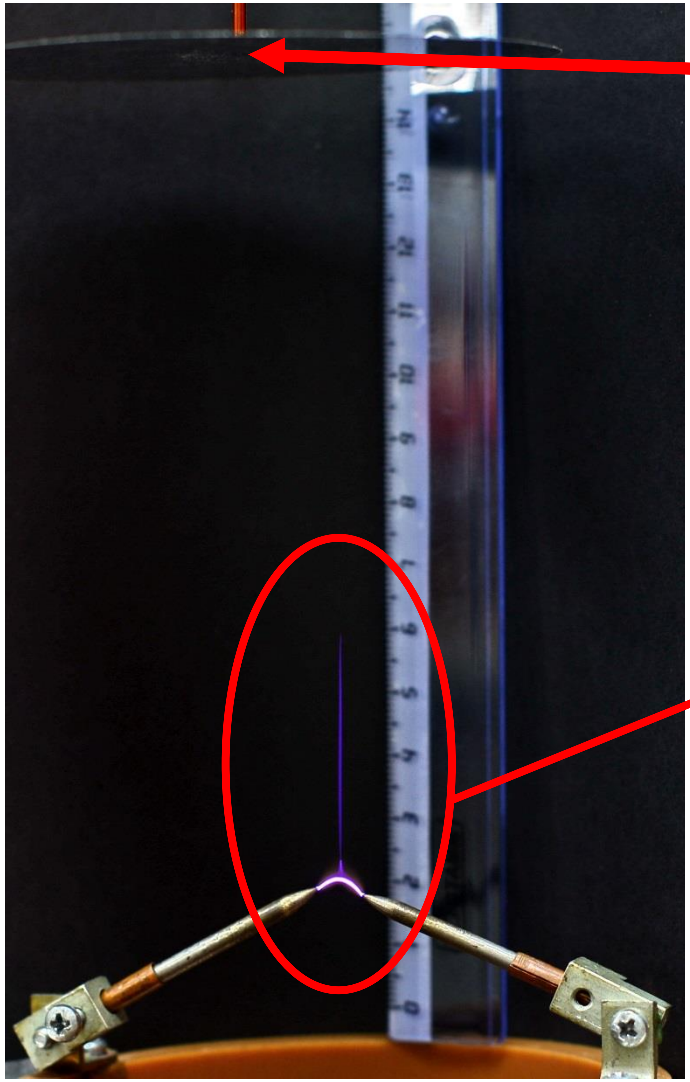
Extra ground (far) electrode gives transversally directed weak electric field of ~ 1-2 kV/cm (much less than the breakdown value), but…

…as could be seen the tip of apokamp channel have a characteristic value of electric field around ~20 kV/cm i.e. sufficient to effectively ionize the surrounding gas and propagate into non-ionized space

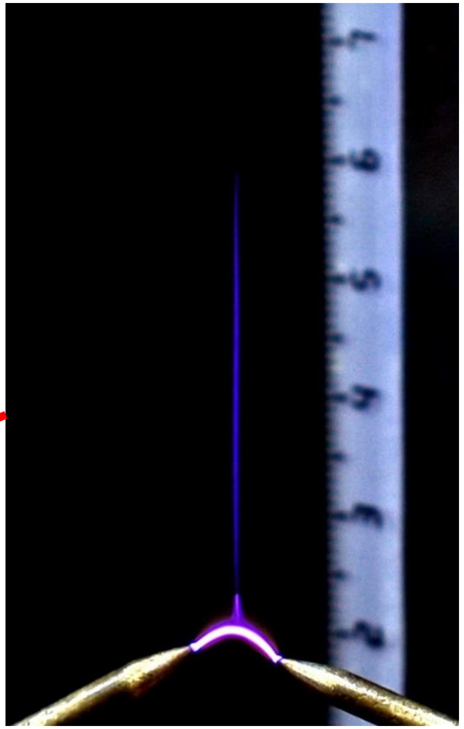
It is known that the local field amplification coefficient at the top of a long conductive rod strongly depends on the ratio of the length l to the radius r: $\boldsymbol{K \sim l/r}$, namely this effect causes an apokamp growth

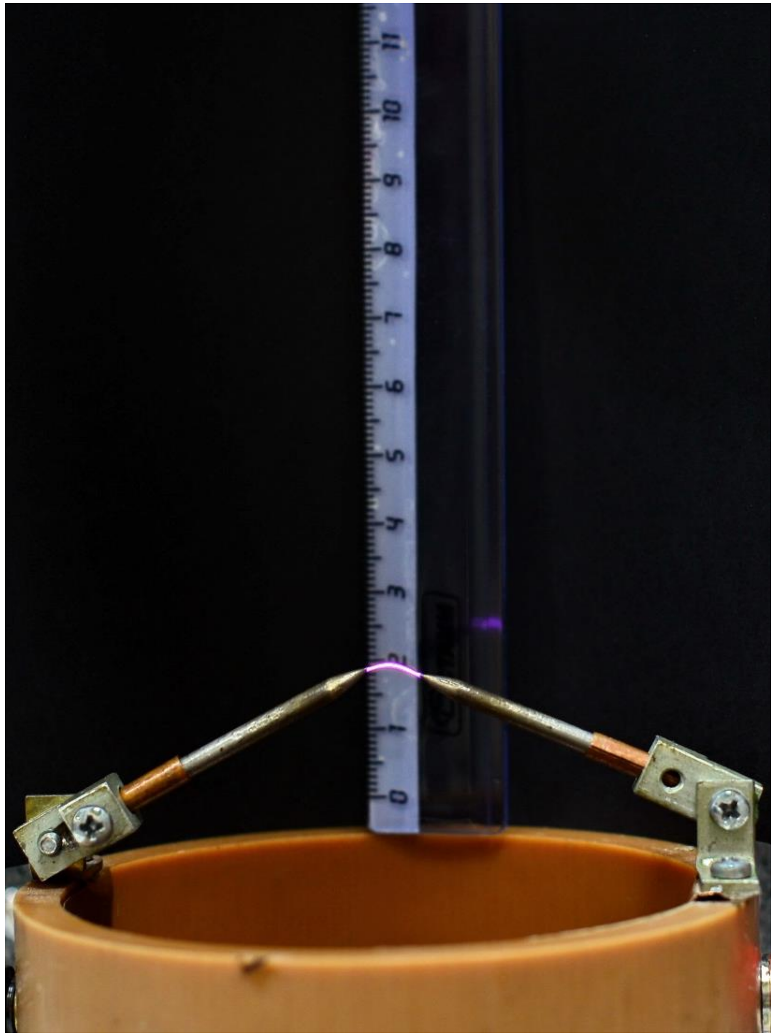


Supporting experiment: Setup



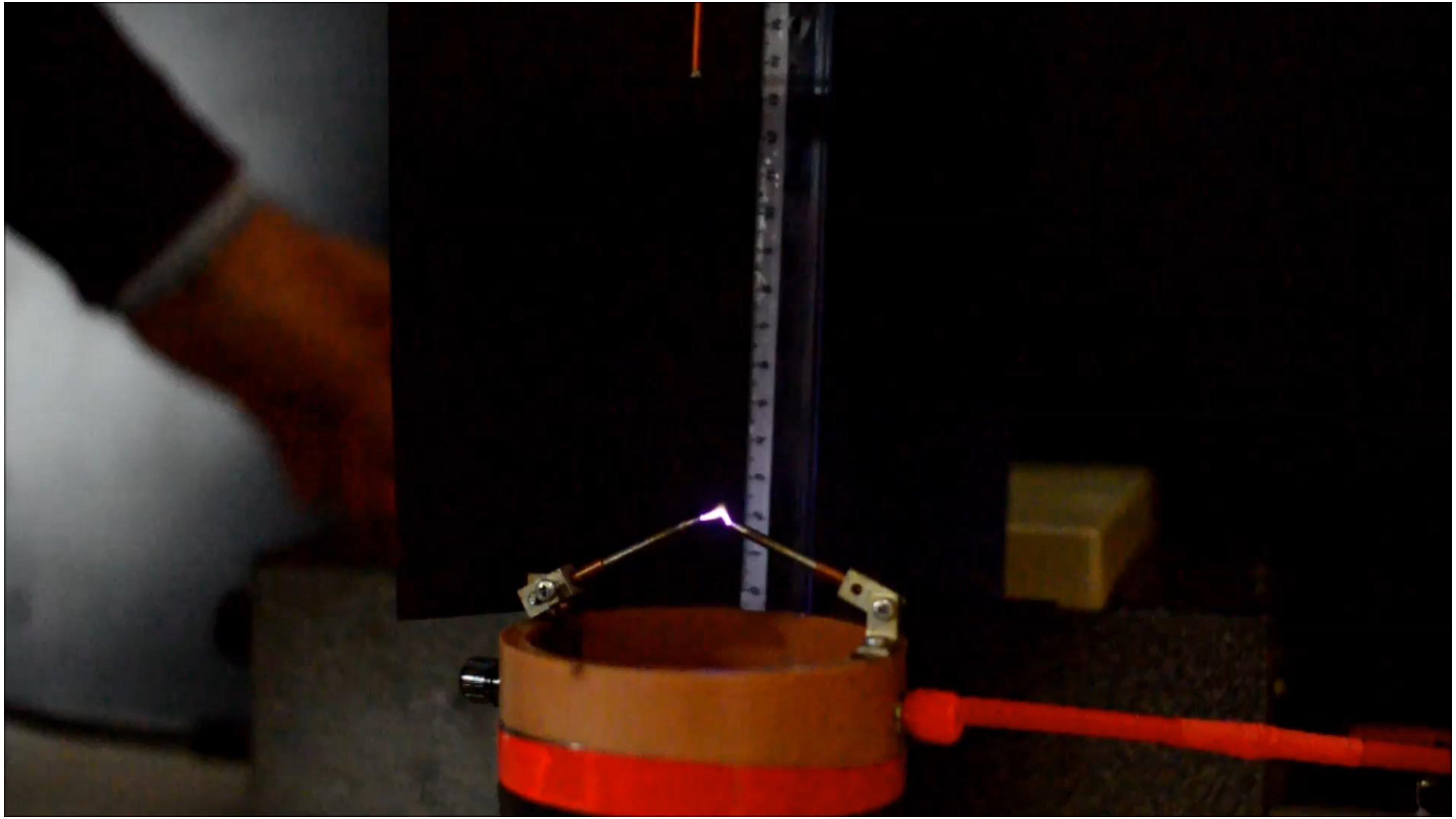
Third electrode





Without third electrode

Supporting experiment: Video



Summary & Conclusions

- The apokamp growth was numerically simulated for a single pulse of HV power supply in oxygen in two-dimensional spatial configuration. It was shown the apokamp is a type of positive streamer that propagates from the top of bended arc channel (between floating and HV electrodes) toward third (grounded) electrode. The physical meaning of the third electrode is in the formation of a weak (pre-breakdown) electric field in the transversal direction, i.e. directed towards the apokamp jet;

- The critical role of a floating-potential electrode in the formation of a high voltage discharge channel was shown. It is necessary to create high potential at the arc in order to initiate an apokamp growth;

- We suggest that delayed start of apokamp formation (after 1000-1200 voltage pulses) is connected with slow heating of near-electrode space to temperatures around 1000-1100 °C

- The simulation also shows the important role of ion-ion plasma of an electronegative gas in the formation of a slowly decaying kernel of the apokamp base

- The apokamp phenomenon was simulated for the first time in COMSOL Multiphysics (!!!)

Thank you!