Analysis of initial stage of capillary discharge using numerical simulation

M.Timshina[1], S.Eliseev[2], N.Kalinin[1], V. Burtsev[1], A. Samokhvalov[3], K. Sergushichev[4], A.Smirnov[4], D. Belsky[2], M. Letunovskaya[2]

[1] *Ioffe Physical Technical Institute, Russian Academy of Science, St.Petersburg, Russia*
[2] *«Burtsev laboratory» limited company, St.Petersburg, Russia*
[3] *ITMO University, St. Petersburg, Russia*
[4] *Saint-Petersburg Electrotechnical University "LETI", Saint-Petersburg, Russia*

Introduction

Capillary discharge is one of the few ways to create highly ionized dense plasma in laboratory conditions. Such kind of plasma is considered as a promising basis for compact sources of X-ray and extreme ultraviolet radiation for nanomicroscopy and lithography [1,2].

Capillary discharges are created with voltage pulses with ns rise time and 100kV amplitude. Typically, in ceramic tubes with a length of 100mm and a radius of several mm filled with gas, usually nitrogen, argon or xenon, at low pressure of the order of several Torr are used.

On the main stage of capillary discharge compression of plasma column happens. In order to achieve higher efficiency, before application of the main pulse the capillary volume is preionized. To create the initial plasma in the volume some researchers use external circuit with an amplitude typically ranging tens amperes [5,6], but several recent experiments have shown [3,4] that it isn't necessary and discharge ignition can happen just before the main stage without any external circuit. Such ignition is called «sliding discharge» (or «gliding») and it is the object of this work.

"Sliding discharge" here is a form of a fast ionization wave (FIW) [7,8] that are generated in screened dielectric tubes. When high voltage is applied to the powered electrode, electric field in its vicinity becomes high. The field accelerates electrons, which then ionize neutral atoms, resulting in space-charge build-up. When the charge density becomes high enough, plasma channel with their front is formed, then front propagates along the dielectric surface and left plasma behind.

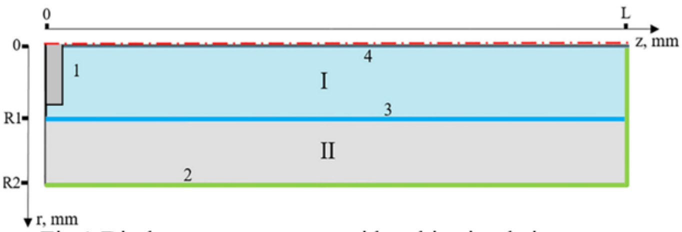

Fig.1 Discharge geometry considered in simulations. Domain I - gas (nitrogen), domain II - dielectric capillary(alumina), 1 - powered electrode (cathode), 2 - grounded boundary, 3 - dielectric surface, 4 - axis of symmetry.

In this paper we present results of systematical numerical simulations of initial stages of capillary discharge –

"sliding discharge" for difference voltage pulse rise time and gas pressure. In results one can clear distinguish the initiation and propagation processes. Simulations have been performed for the case of a 10 cm long alumina capillary filled with non-preionized nitrogen gas. Based on it we estimated some of this parameter's influence on the wave propagation.

Model description

Our investigation is devoted to a discharge in an long alumina capillary with inner radius R_1=2.5 mm, outer radius R_2=10 mm and length L=100 mm filled with nitrogen at low pressure. At one of the capillary ends metal cylindrical cathode is placed, at another end – anode on which zero potential is applied, besides, external capillary surface is also grounded. To the cathode potential with 10kV constant amplitude with several ns rise time is applied. The problem is considered in 2D axially symmetric formulation, scheme of geometry of used numerical model is presented in Fig. 1.

The numerical model was based on self-consistent system of balance equations for charged particle densities written in drift-diffusion approximation and Poisson's equation for electric potential. All transport coefficient are the functions of reduced electric field and have been obtained from the solution of Boltzmann equation in two-term approximation. A more detailed description of the model is presented in [9].

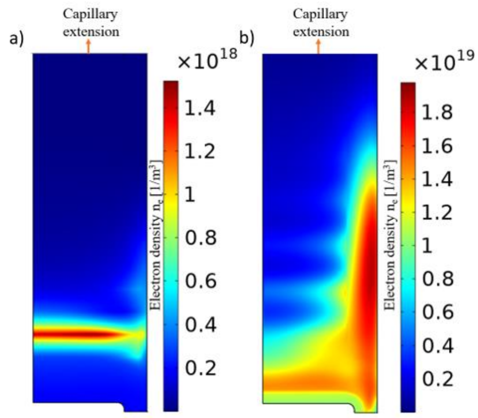

Fig.2 Spatial distributions of electron density n_e showcasing the wave initiation process for a)3ns and b)3.8ns for the case of 2Torr and 5ns voltage rise time.

Pressure, Torr	Initiation time, ns
0,5	"-"
2,0	3,8
3,0	2,2
4,0	1,8
5,0	1,5
8,0	1,2
25,0	1,0
80,0	1,4

Tab.1 Dependence of initiation time on gas pressure for the case of 2Torr and 5ns voltage rise time.

Results and discussion

This paper presents the results of the model described above for different voltage pulses rise times and in a wide range of low pressure. As a base case we take pressure of 2Torr and 5ns rise time.

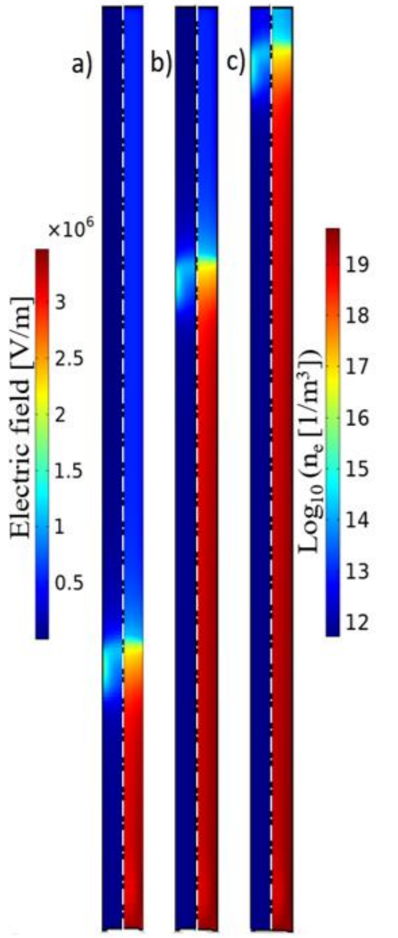

Fig.3 Spatial distributions of electric field intensity and logarithm of electron density showcasing the wave propagation process for a)5.4ns, b)8.5ns, c)10.3ns for the case of 2Torr and 5ns voltage rise time.

First, we should notice that two stage of sliding discharge can be distinguish: initiation and propagation. Short circuit (the moment when plasma reach the anode) will be considered as a sliding discharge ending, after that, properly speaking , sliding discharge develops into another kind of discharge.

Figure 2 shows spatial distributions of electron density in the vicinity of the cathode for the moment before and just after initiation. It can be seen that it takes some time before electrons start accumulating on dielectric surface. Then ionization increases in the vicinity of the dielectric surface that forms the front of the ionization wave of sliding discharge. In table 1 we can see the dependence of initiation time on gas pressure. Local minimum(~25Torr) of this dependence can be perceived as a reflection of Paschen's law but in such complicated geometry. Also below some pressure(~0.5Torr) value the discharge forming doesn't happen what is connected with insufficient space localization of charge particle.

Further let us consider the wave propagation along the capillary. Fig. 3 shows the picture of full space inside the capillary where on the left half spatial distributions of electric field intensity are presented and decimal logarithm of electron density on the right half for different time. The maximum of electric field characterizes the location of the discharge front, behind it plasma channel occurs.

The most important results are presented on fig.5. Fig.5a) shows overall dependence of sliding discharge time on pressure. The local minimum of this dependence comes as a result of different influence of pressure on the initiation and propagation processes. Green area indicates the case when initiation time is greater than propagation time, yellow area – the opposite situation. Dependence of sliding discharge time on voltage rise time is presented on fig.5b). Two cases can be distinguished here: when sliding discharge shorts the gap before voltage reaches it's maximum value (yellow area) and when it shorts the gap after(green area). In the latter case the discharge current will have higher value, that could influence positively the main capillary discharge stage.

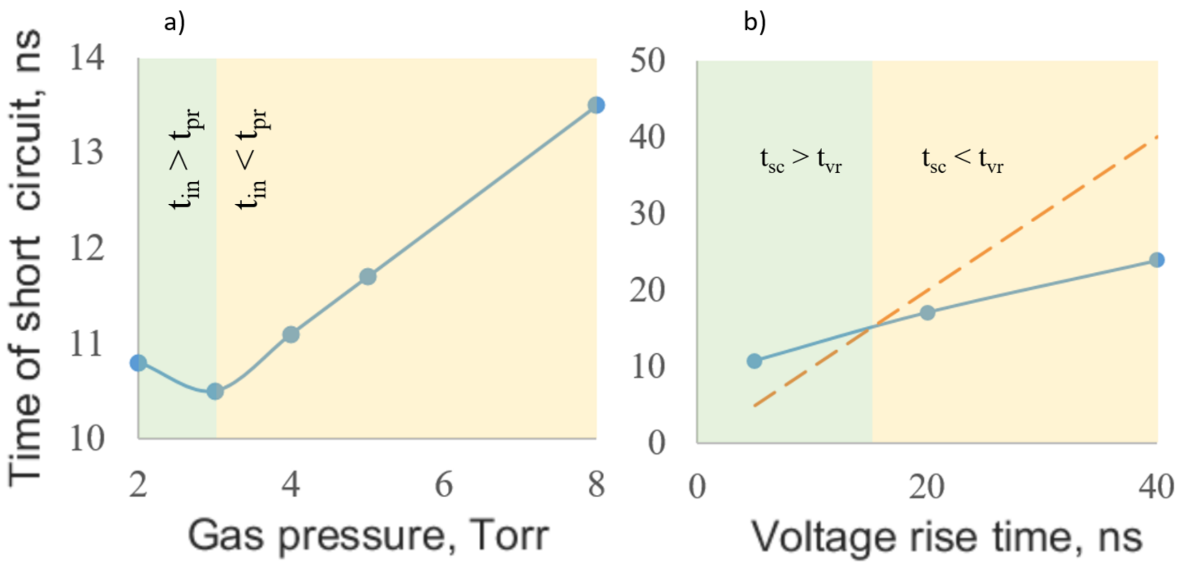

Fig.4 a) Pressure dependence of the short circuit time for fixed voltage pulse with 10kV amplitude and 5ns rise time; b) Voltage rise time dependence of the short circuit time for 10kV voltage amplitude and 2Torr.

Conclusion

In present work numerical simulations of a sliding discharge in nitrogen in a capillary have been performed at low pressure, based on fluid approach with drift-diffusion approximation. Discharge dynamics was analyzed where attention is paid to two stages of sliding discharge – initiation and propagation. Dependence of total sliding discharge time on gas pressure and voltage rise time for amplitude of applied voltage of the order of several kV was presented. Both dependence show different cases of sliding discharge behavior regarding of ratio of initiation time to propagation time for the first dependence and ration of sliding discharge time to voltage rise time for the second dependence.

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