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Electrode Configurations and Non-uniform Dielectric Barrier Discharge Properties

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Abstract: Interesting types of *AC* discharges in ambient air at atmospheric pressure for the generation of non-thermal plasma at/on dielectric surfaces were investigated. *Pin-to-plane dielectric barrier discharge (PTP-DBD)* was sustained in the electrode configurations combining electrode components of both corona and *DBD* - metallic pins, or triangle spikes electrode, situated single- or double-in-line and metallic plate electrode covered with a dielectric barrier. It was investigated experimentally and theoretically the burning mode of a *PTP-DBD* in ambient air at atmospheric pressure. The *PTP-DBD* behavior with single- or double-in-line spikes high voltage electrode was discussed. The *PTP-DBD* is a new *DBD*-based discharge.

Keywords: burning voltage, critical parameters, dielectric barrier discharge, non-uniformity, operating area, single- and double-in-line spike electrode.

1 Introduction

Cold plasmas generated and maintained at atmospheric pressure (760 ± 25 Torr) and room temperature enjoyed a renaissance after the 1980s - besides thermal plasmas such as high-intensity arcs, plasma torches, and radio-frequency discharges, also this non-equilibrium plasmas are of great interest due to the increased number of its industrial applications as surface plasma and plasma-aided materials processing, [1].

From the early history of gas discharge physics it was apparent that, after ignition of the discharge, entirely different plasma states can be established in the same medium. One of representative was the hot arc discharge, approaching conditions of *local thermodynamic equilibrium (LTE)*. In short, this thermodynamic state is

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characterized by the property that all particle concentration are only a function of the temperature, or these plasmas are also referred to as *thermal plasmas*.

The second representative was the *non-equilibrium cold plasma* of dielectric barrier discharge (*DBD*) that is characterized by the property that the energy is selectively fed to the electrons leading to electron temperature that can be considerably higher than the temperature of the heavy particles T_g in plasma - neutrals and ions ($T_e >> T_g$). This non-equilibrium, or *non-local thermodynamic equilibrium (non-LTE) plasma*, exhibits typical plasma properties such as electrical conductivity, light (*UV*) emission and chemical activity already at moderate gas temperature, even at room temperature (Drawin, 1971). In extreme cases the electron temperature can reach well above 20 000 K while the gas temperature stays close the room temperature. Non-equilibrium cold *DBD* plasma has found important and far-reaching technical applications, [2].

2 Pin-to-Plane Dielectric Barrier Discharges

In contrast to a glow-discharge, the *DBDs*, at low frequency (50 Hz) and atmospheric pressure, consist of a large number of bright filaments distributed in the discharge gap, so called ”families” of microdischarges. These filaments are actually microdischarges that repeatedly strike at the same place as the polarity of the applied voltage changes, thus appearing as bright filaments to the observer’s eye.

Interesting types of atmospheric pressure *AC* air discharges for the generation of non-thermal plasma at/on dielectric surfaces were published recently (Akishev et al, 2002; Radu et al, 2003). These discharges are sustained in the electrode configuration combining the electrode elements of both: corona - metallic pins and plane, and *DBD* - metallic plate electrodes and one of them covered with a thin dielectric barrier and called *alternative current barrier corona (AC-BC)* or *pin-to-plane DBD*. The authors investigated experimentally and theoretically the burning mode of a pin-to-plane *DBDs* in ambient air and different gases at atmospheric pressure. Diverse applications demand a solid physical and chemical understanding of the operational principals of such discharges, [3].

In the following paper the overall discharge behavior of a new *DBD*-based discharge - a pin-to-plate *DBD* configuration, used to produce cold plasma was discussed with special emphasis on the influence of electrode configuration on the electrical characteristics respectively on the static (external) volt-ampere characteristics and operative areas and sub-areas.

3 Experimental Investigation

The classic low frequency *AC DBD* consists basically of two planar electrodes (sometimes co-axial or adjacent cylinder) made of two metallic plates (or tube), one of them or both covered by a dielectric materials and separated by a variable gas or air gap, Fig. 1a. The electrodes are energized by a HV power supply with typical voltages in the $1 \div 20$ kV range and industrial frequency (50 Hz). The edge effect is used for establish AC *non-uniform DBD*, Fig. 1b, [3].

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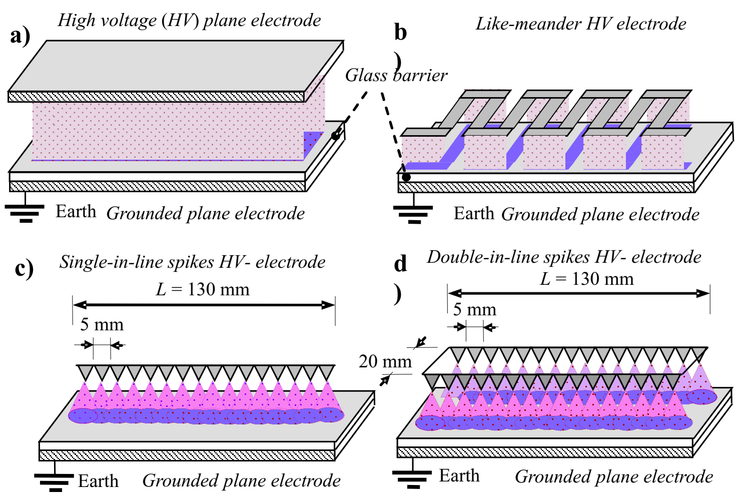

Fig. 1. Electrode configurations of dielectric barrier discharge *(DBD)*: **a** - typical *plate-to-plate* (or co-planar) *DBD* with one metallic electrode covered with a dielectric barrier; **b** - *edge effect DBD* with local non-uniformity of meander like high voltage electrode; **c** - *pin-to-plate DBD* or *AC barrier corona* with *single-in-line* spikes high voltage electrode; **d** - *pin-to-plate DBD* with *double-in-line* spikes high voltage electrode.

The *pin-to-plate DBDs* are typical discharges with expressed local non - uniformity closeness high-voltage electrode that consists a lot of spikes arranged the length of electrode according two way - *single-in-line* or *double-in-line*, Fig.1c and d. An alumina profile is used for making the two studded high voltage electrode configurations with *single-in-line (SIL)* and *double-in-line (DIL)* arranged spikes, Fig.2.

Electrode configuration is in position to provoke various schemas of electromagnetic interaction between microdischarges. This electrodes geometry effect (*EGE*) needs a change in microdischarges self-organization, and different ”crystal” patterns in *DBD*-based discharges. It exerts strong influence on the breakdown conditions and avalanche transformation into a streamer that have to modify the *DBD’s* volt-ampere characteristic, ignition U_b voltage, and critical parameters of operating (oxygen and nitrogen) sub-areas, Fig.3.

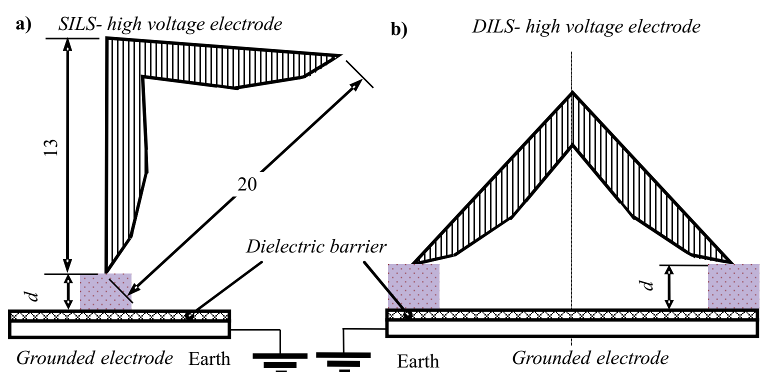

Fig. 2. *Pin-to-plate DBD* electrode configurations set the properties of *DBD*-based discharge: **a** - *single-in-line* arranged spikes (*SILS*) electrode, and **b** - *double-in-line* arranged spikes (*DILS*) electrode.

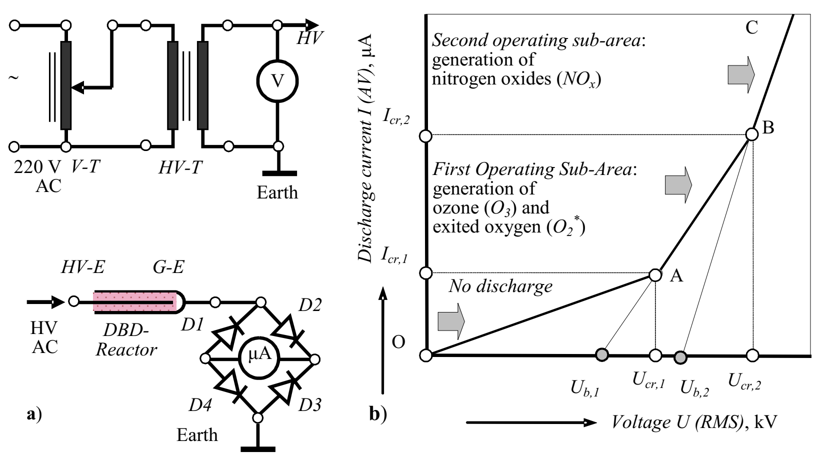

Fig. 3. Dielectric barrier discharge (*DBD*) configuration for plotting static (external) volt-ampere characteristics - the relationship between the average of discharge currents and the *RMS* of voltage (**a**) and linear polygonal model of static volt-ampere *DBD* - based discharges characteristic (**b**).

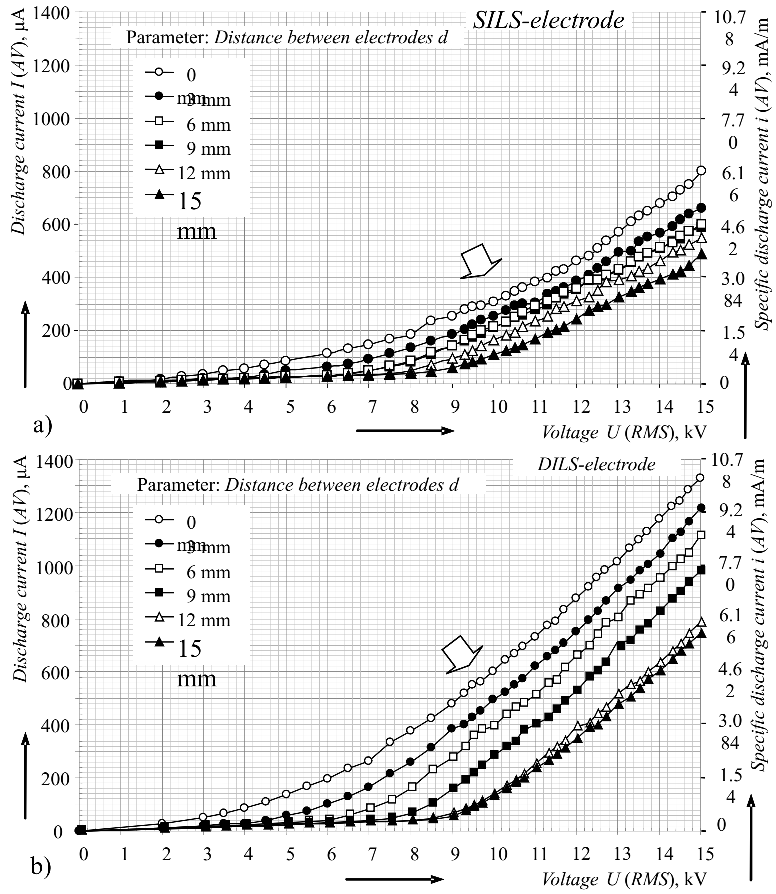

Fig. 4. Families of experimental static volt-ampere characteristics of two investigated electrode configurations of *pin-to-plate DBD* with: **a** - *single-in-line spikes (SILS-)* electrode; **b** - *double-in-line spikes (DILS-)* electrode.

It is involved that the local non-uniformity provoked by arranged in (one or two) line spikes will modify the *pin-to-plate DBDs* electrical external characteristic and parameters depending on the operating condition - the inter-electrode gap distance. We believe that the small gap distances will give rise to the typical influence of local non-uniformities on electrical characteristics and parameters of *pin-to-plate DBDs*.

4 Results and Discussion

The external characteristics of *pin-to-plane DBDs* have been plotted experimentally, Fig. 3a and 4, linear polygonal discharge models, Fig. 3b, have been worked

Table 1. Linear polygonal models of static volt-ampere characteristic of *pin-to-plate DBD*.

Regression equations		Name of DBD operation area	Slope B	Intercept A	Correlation coefficient r
			μA/kV	μ A	-
Single in line spikes electrode system					
Inter-Electrode Distance d	0 mm	0-1	21.627	-27.427	0.9980
		0-2	30.327	-65.673	0.9990
		0-3	64.657	-324.611	0.9970
		0-4	109.306	-850.093	0.9976
	3 mm	3-1	39.582	-153.993	0.9930
		3-2	83.054	-570.706	0.9960
	6 mm	6-1	70.924	-488.327	0.9969
	9 mm	9-1	69.207	-462.349	0.9958
	12 mm	12-1	71.916	-545.437	0.9962
	15 mm	15-1	67.277	-552.034	0.9926
Double in line spikes electrode system					
Inter-Electrode Distance d	0 mm	0-1	35.440	-56.820	0.9988
		0-2	58.724	-154.110	0.9976
		0-3	100.848	-428.493	0.9972
		0-4	126.166	-655.852	0.9987
		0-5	150.116	-926.412	0.9996
	3mm	3-1	38.257	-132.743	0.9973
		3-2	57.760	-245.720	0.9989
		3-3	101.219	-546.446	0.9979
		3-4	124.165	-747.338	0.9988
		3-5	151.764	-1070.114	0.9989
	6 mm	6-1	107.359	-670.693	0.9944
		6-2	145.694	-1083.791	0.9981
	9 mm	9-1	118.599	-864.872	0.9881
	12 mm	12-1	115.338	-988.288	0.9907
	15 mm	15-1	5.080	-1.673	0.9998
		15-2	109.442	-942.884	0.9889

out in accordance with [2], for a minimal coefficient of linear correlation, not less than 0.9900, and then all the electrical parameters of the non-operating area, first and next *DBDs* operating areas have been calculated, Table 1.

A specific discharge current *i* for unit length of electrode configuration (μA/m or mA/m) is obtained on the base of the same length of experimental electrodes - $l = 130mm : i = I/L$, mA/m. There are in a unit (1 m) electrode length 200 spikes arranged in single-in-line therefore the specific current per spike is: $i_{sp} = i/200$ or for example when *i* = 1 mA/m the specific discharge current per spike is 0.005 mA (5μA). For *SILS- pin-to-plane DBDs*, the maximal specific current (d = 0; 200 spikes per one meter, on the surface of glass barrier) per spike (voltage less then 15

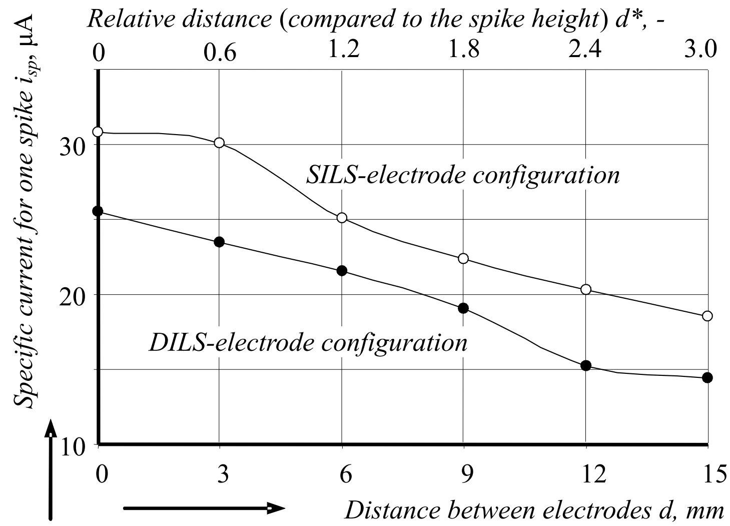

Fig. 5. The specific current per spike i_{sp} depending on the distance *d* between the electrodes and *SILS*- and *DILS*-electrode configurations.

kV!) is $i_{sp} = 30.8\mu$A, while for *DILS- pins-to-plane DBD* it is at same conditions (but 400 spikes per one meter, on the surface of glass barrier) $i_{sp} = 25.5\mu$A. If there is an electrode configuration with the same number of spikes (400) but single-in-line arranged (2 meters length) then the specific current per spike will be $i_{sp} =$ 61.4μA or 17.2% higher. The linear distance between two adjacent spikes is $l =$ 5mm, and the distance between two adjacent lines is $b = 20$mm or $b = 4.l = 4.h$, Fig. 2a. It exist an interaction between the local spike microdischarges of adjacent lines in spite of the relatively large distances - four times the height of particular spike, for the different distances between electrodes, Fig. 6. If this examination will be applied for unit length of the electrode configuration (per one meter) then *DILS*- configuration has its advantage: the specific discharge current is higher with more then 50%.

Ordinary the external volt-ampere characteristics of *plane-to-plane* (co-planar) *DBDs* are represented by polygonal linear models with tree sub-areas that correspond with the main development stages of discharges - the stage preceding the *DBDs* ignition, (non-operating area); and the first and the next stages of burning *DBDs* (operating area with its sub-areas). The external volt-ampere characteristics of *pin-to-plane DBDs* at low inter-electrode distances are represented by polygonal linear models with more then tree sub-area, Table 1.

The generalized model of burning *pin-to-plate DBDs* has the following special feature common for all *DBD*-based discharges: *i)* the *pin-to-plane DBD* burns at a constant burning voltage, i. e. U_b = const; *ii)* the ignition of *pin-to-plane DBD* or

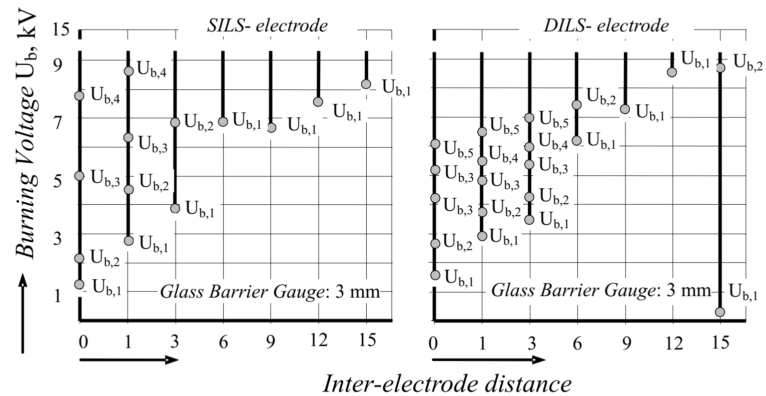

Fig. 6. Burning voltage Ub for different operation areas ($U_{b,1}$, $U_{b,2}$, $U_{b,3}$, $U_{b,4}$ and $U_{b,5}$) and electrode configurations (*SILS*- and *DILS*-) of *pin-to-pin DBD*.

the transitions to a new operating area are threshold processes occurring for certain critical parameters - voltages and currents (U_{cr} and I_{cr}); *iii)* the *pin-to-plane DBD* have to be described by the linear relationship between the average of the discharge current and the *RMS* of voltage - the coefficient of linear correlation gets values over 0.9881, and above 0.9900 at low inter-electrode distances, Table 1.

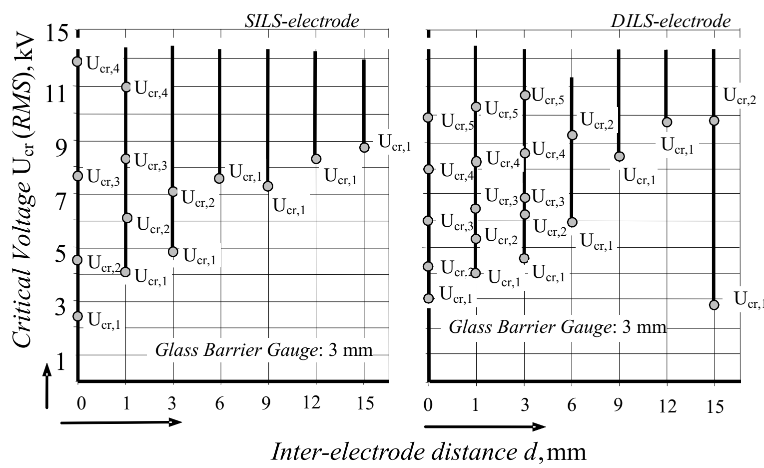

Fig. 7. Ignition (or critical) voltage U_{cr} for different operation areas ($U_{cr,1}$, $U_{cr,2}$, $U_{cr,3}$, $U_{cr,4}$, and $U_{cr,5}$) and electrode configurations (*SILS*- and *DILS*-) of *pin-to-pin DBD*.

The model is based on following linear equation - $I(AV) = B.U(RMS) + A$, where B is the slope and A - the intercept of the geometric line.

5 Conclusions

As a result of the experimental investigations by the static electrical characteristics and electrical parameters of operating sub-areas performed for two electrode configurations of *pin-to-plate DBDs*, the following main conclusions can be derived:

- The electrode configuration effect or the influence of the local non-uniformity on DBD-based discharges does exist and can be successfully applied creating more effective plasma technological systems;
- The *pin-to-plane DBD*, or *AC barrier corona (AC BC)*, is a typical *DBD*-based discharge and this fact is very good shown when there are large inter-electrode distances. Then the operating area is constituted also by two operating sub-areas typical for *plate-to-plate (co-planar) DBDs*, or pseudo-uniform *DBDs*: the first or oxygen operating area generates ozone and oxygen containing cold non-equilibrium plasma, and the second or nitrogen operating area generates nitrogen oxides (NO_x) containing non-equilibrium plasma. The same elementary processes in the inter-electrode space of *pin-to-plate DBDs* are able to exist. The assumption that the *pin-to-plane DBD* is *DBD*-based discharge is fully acceptable or the described properties of *pin-to-plate DBD* are common to all *DBD*;
- The *pins-to-plate DBDs* burn in every operating sub-area at constant burning voltages U_b. This is a distinguishing feature for all the *DBDs*. That fact put also the *pin-to-plate DBD*s in the family of *DBD*-based discharges;
- The specific behaviour of *pin-to-plate DBD* is well shown at small inter-electrode distances - less then 6 mm. The operating area is constituted by more then two operating sub-areas - tree, four and five areas. That's the effect of electrode configurations that introduce a local non-uniformity nearness to high voltage electrode. The small inter-electrode distances manifest the effect of local non-uniformity on external characteristics and electrical parameters of *pins-to-plate DBD*;
- The *double-in-line spikes (DILS)* arrangement created by the use of a specific aluminum profile is a good technical decision because it suggests better discharge parameters - lower ignition U_{cr} and burning U_b voltages;
- The method of mathematical description of *DBD* static volt-ampere characteristics by linear polygonal models is applicable to the *pin-to-plate DBDs*. The coefficient of linear correlation gains values about unity: from 0.9926 to 0.9998 for different electrode configurations, inter-electrode distances and operating areas. There is a strong functional subordination between the average of discharge currents and the *RMS* of voltages;

- The present research formulates the problem of the electrode configuration influence and local non-uniformity on the elementary processes in cold non - equilibrium plasmas, external electric characteristics and parameters.

Acknowledgements

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