Statistical analysis of microgap vacuum breakdown mechanisms for palladium electrodes in pulsed electric fields

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For uniform treatment of samples, it is essential to ensure the homogeneity of plasma. One of the ways how to achieve homogeneous plasma is by generation it within micrometric distances between electrodes. The first attempts to characterize phenomena of micrometric discharges were performed by Boyle, Germer, Kisliuk, and others [1,2,3]. They investigated the question of the origin of microgap discharge breakdown and field emission phenomena connected with it, mostly from a fundamental point of view. However, studying microdischarges at high pressures poses technical challenges due to the complex nature of field emission phenomena resulting from fast ionization processes within the discharge region. The solution to this can be found by working in a vacuum environment, where the influence of the carrier gas could be neglected.

In general, the field emission processes occurring in the pre-breakdown stage seem to be crucial for microgap vacuum breakdown initiation mechanisms accompanied by high electric fields. Despite numerous papers investigating these processes, they remain relatively unexplored and require deeper analysis [2,4,5]. In our previous work, we investigated field emission phenomena from stainless steel (SS) [6]. This study show a significant influence of high temperature due to the low thermal conductivity of SS. Following this research our focus has shifted to metals characterized by higher thermal conductivity, representing groups of noble metals. Despite the utilization of noble metals like palladium or iridium in spark plugs, there is a lack of available data describing breakdown processes. The objective of this work is to statistically characterize the breakdown and pre-breakdown stages for a better understanding of occurring mechanisms. Before conducting experiment, the conditioning of electrodes is needed. This process involves cleaning the electrodes from impurities by generating successive breakdowns between them, which is accompanied by an increase in breakdown voltage as shown in Fig. 1. The electric breakdowns were generated by a pulsed electric signal with a voltage ramp speed of 10^7 kV/s. The gap between electrodes was set at 10 µm. When the average breakdown voltage stabilized (saturated), the electrodes are considered to be conditioned, as represented in Fig 1.

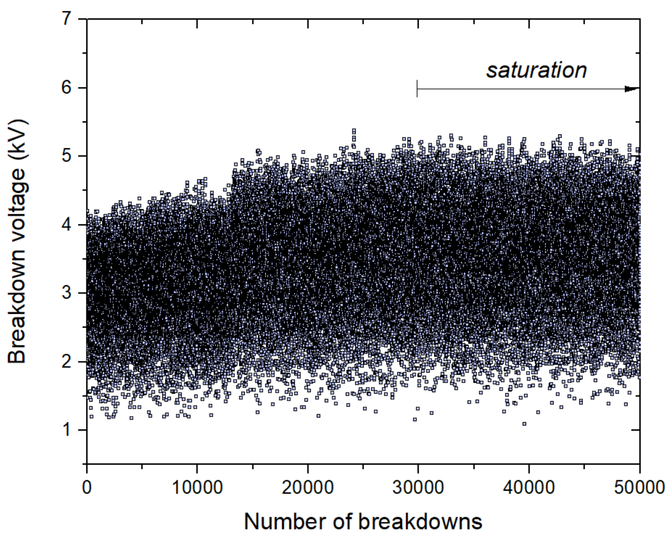

Fig. 1: The evolution of the breakdown voltage during conditioning process (10^7 kV/s, 10 µm).

One of the objectives of our statistical analysis was to investigate the relationship of the sequence of successful consecutive breakdowns, for samples over 10,000 sequences, measured in the saturated stage. To illustrate, the voltage-current waveform of one sequence (burst) is represented in Fig. 2. The length of the sequence (burst duration) was set at approximately 3 µs and contained several breakdowns.

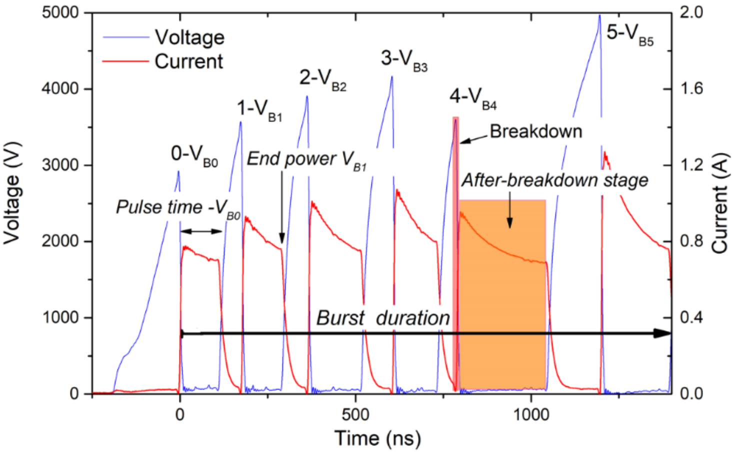

Fig. 2: The typical voltage-current waveform of the pulse sequence with several breakdowns.

For visual representation, we present a density scatter plot showing the dependence of breakdown voltage V_{Bi} on the difference between the subsequent breakdown voltage $V_{B(i+1)}$ and the previous breakdown voltage V_{Bi} for every sequence. The index i (i = 0,1,2,3...) represents the number of the breakdown in the sequence. The Fig. 3 illustrates the pattern 1-0 (for index i = 0, i. e. V_{B1}-V_{B0} versus V_{B0}) which represents the relation between the first and second breakdowns in the sequences. From Fig. 3, it can be observed that the initial breakdown in the pulse sequence (index i = 0) is most likely to occur within the range of 3 kV to 4.1 kV, with a subsequent probable increase to approximately 50-450 V. If the initial breakdown voltage was above 4.4 kV, the next breakdown voltage decreased to the range of 1kV to 3kV. Interestingly, a similar pattern was observed in all subsequent pairs of breakdowns in all pulse sequences (2-1, 3-2, 4-3). This leads to the conclusion that within the low voltage span (in this case, 3-4kV), there is a gradual step increase in V_{B0}.

The scatter density plot results clearly illustrate an observable relationship between successive breakdowns. If the initial breakdown begins in the low voltage region, the next breakdown increases in several voltage steps, ending with a large drop proportional to the maximum breakdown voltage This observation strongly suggests the presence of a memory effect between two consecutive breakdowns.

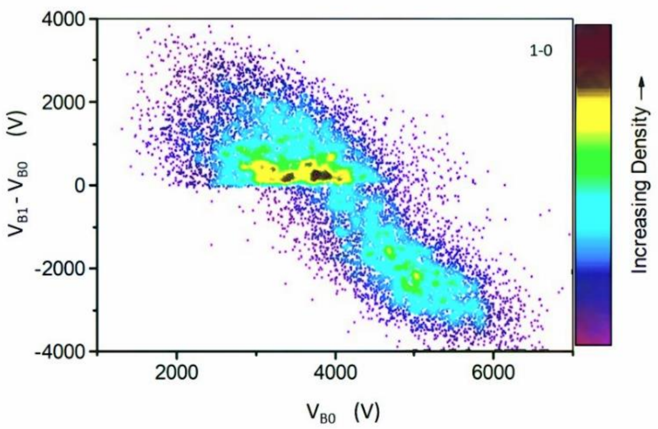

Fig. 3: The density scatter plot of $V_{B1} - V_{B0}$ versus V_{B0} representing the memory effect of two subsequent breakdowns (for 10 μm).

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