Comparative Study of Electrical Insulation in Vacuum at DC and Pulsed Voltages *

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Abstract – The paper is devoted to study of mechanisms responsible on vacuum breakdown at low (20 kV) dc and high (200 kV) pulsed voltages applied to the same electrode surfaces to recognize how dc voltage measurements correlate to phenomena at high pulsed voltages. Breakdown tests at 100-ns pulse voltages demonstrated the total voltage effect while prebreakdown currents at dc voltages don't depend on the total voltage. The strong dependence of hold-off on anode temperature was recognized at dc voltages while pulsed hold-off turned out to be almost the same with heating electrodes. The latter gives a basis to consider gas desorption as an insufficient factor in initiation of pulsed breakdown.

1. Introduction

In the course of experiments on anode-probe scanning of cathode surfaces [1] correlations of prebreakdown currents to breakdown events were recognized in a case of mechanically polished electrodes which surfaces contain numerous irregularities like foreign material inclusions. In that case prebreakdown emission got active at static electric fields close to hold-off at pulsed voltages; and breakdowns located at surface irregularities. Quite another situation took place with using electrodes subject to electron beam surface treatment (EBEST) in the mode of pulsed surface melting in vacuum. Prebreakdown emission onset at low (20 kV) dc voltages was recognized at electric fields, E_{on}, essentially higher than hold-off, E_{br}, at high (230 kV) pulsed (~ 100 ns) voltages. EBEST electrodes demonstrated the total voltage effect (TVE) at short-pulse voltages [2] when E_{br} falls with gap length, d, as $d^{-1/2}$, and this fact could explain tentatively the difference. Correlations in location of breakdown events and prebreakdown sites were also absent in a case of EBEST electrodes.

The total voltage effect was recognized long ago to affect prebreakdown emission also [3,4,5]. This fact caused our interest to check whether TVE on prebreakdown current takes place in our experimental conditions.

Our interest concerns also attempts to treat EBEST electrodes by additional techniques to sustain prebreakdown conductivity and enhance hold-off. First of all, breakdown tests were carried out for red-hot electrodes. This was undertaken to explore the role of adsorbed gas in initiation of short pulse breakdown.

2. Experimental

All the experiments were performed in conditions of high oil-free vacuum of about 5×10^{-7} mBar and in dust-free air environment. Plane electrodes with rounded edges were made of either 304L stainless steel or 45N nickel-iron alloy (45% nickel). Electrodes were wiped with a lint-free cloth and acetone after preliminary treatment that was either mechanical polishing or EBEST. The experimentation was carried out with low-voltage dc and high-voltage pulse arrangements.

The low-voltage dc arrangement was based on the anode-probe scanning technique described recently elsewhere [1] in details. The arrangement is shown in Fig. 1 schematically.

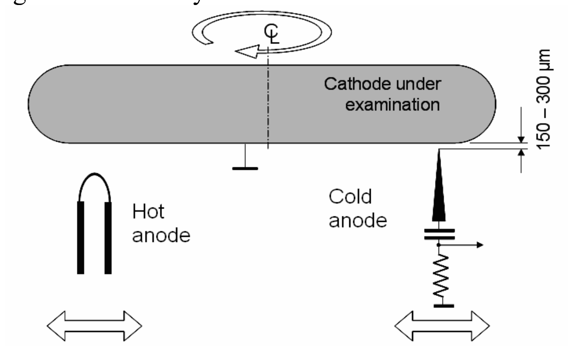

Fig.1. Experimental arrangement for dc voltage experiments

A part of measurements of dc hold-off at narrow gaps were carried out with a yellow-hot incandescent anode to value significance of gas desorption in conditions under the experimentation.

The high-voltage pulsed technique used in the work has been described in details elsewhere [1], and no changes were made except of electrode holders and

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electrodes that were upgraded to allow heating above 700 C. In brief, the Marx generator with high-voltage pulse amplitude of 220 kV, impedance of 200 Ohm, and pulse duration of 60±10 ns was used to test vacuum insulation. High-voltage pulses were applied to an anode. The start gap length was chosen to exclude occasional breakdowns with a first voltage pulse. Gradual (50 – 100 μm step) rapprochement of electrodes with high-voltage pulse firing on each step was carried out until breakdown occurs. First breakdown electric field strength, E_{br}^{1}, and maximal breakdown electric field strength within a test protocol, E_{br}^{max}, were recorded for further considerations.

As a matter to recognize the nature of emission sites, experiments with artificial sites were carried out. Emission sites of two kinds were used, which are as follows: a stainless steel needle with tip radius of about 20 μm and a simulator of a MIV site (metal-insulation-vacuum), made from a 0.4-mm-diameter stainless steel wire and a glass pipe of much the same inner diameter. The simulating emitters are shown in Fig. 2. The emitters were carefully cleaned just before installation into the test chamber. An emitter was attached with welding to the working surface of a plane cathode at the radius of 3 cm to meet a site rotation under the anode-probe scan protocol.

Fig. 2. Artificial emission sites simulating a metal protrusion (on the left) and a MIV site (on the right)

3. Results and Discussion

3.1 Total Voltage Effect on Prebreakdown Current

Measurements of voltage-current characteristics have been carried out with the anode-probe scanner at gap lengths varied within 80 to 170 μm opposite recognized emission sites. Twelve EBEST plane cathodes were involved in this experiment while only five of them were successful in measuring voltage-current characteristics of prebreakdown currents. The rest of electrodes were broken down under data acquisition. Current-voltage characteristics in the original form are plotted in Fig. 3. Deviation of current in plots is caused mainly by beating a cathode under rotation. The results of analysis of the characteristics using the formalism of the Fowler-Nordheim equation are listed in Table 1.

As a whole, there is no noticeable dependence of prebreakdown current on total voltage at voltages of up to 20 kV. This result disagrees with data presented elsewhere [3,4,5].

EBEST surface was proved earlier [1] to be free of intrinsic non-metallic inclusions. We performed the experiment with an artificial emission site of MIV kind to check whether TVE in respect to prebreakdown currents is the attribute of emission sites associated with dielectric inclusions.

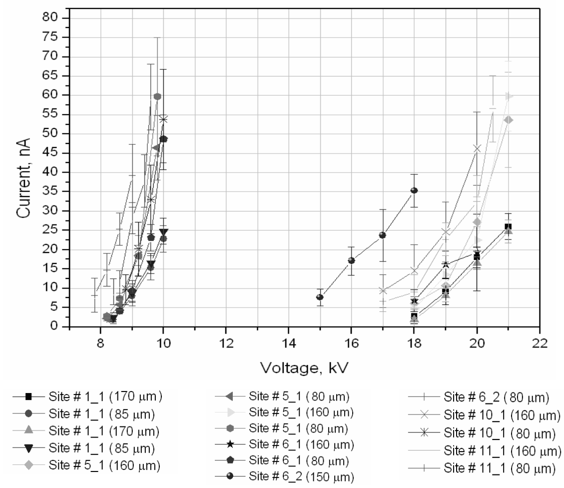

Fig. 3. Current-voltage characteristics of emission sites on surface of EBEST cathode, taken at different gaps and voltages

Table 1. Results of analysis of Fowler-Nordheim characteristics plotted in Fig. 3

Site #	Steel	Rotation rate, Hz	Gap, μm	β	S_{eff}, cm^{-2}
1_1	304 L (hydrogen annealed)	7.3	170	39	1.8E-11
			85	42	6.7E-12
		2	170	34	1.3E-10
			85	46	2.2E-12
5_1	316 L SCQ	8.6	160	36	2.5E-11
			80	32	3.8E-10
		2.6	160	33	1.1E-10
			80	33	2.5E-10
6_1	304 L	7.8	160	32	2.5E-10
			80	34	1.2E-10
6_2		7.8	150	81	1.2E-14
			80	58	4.1E-13
10_1	321 S	6.3	160	61	1E-13
		7.1	80	42	8E-12

Voltages at which prebreakdown current is set to 20 nA were measured with gradual increase of the gap length. Dependence of voltage V_{20nA} on the gap length is shown in Figure 4a. The plot differs from the straight line insignificantly. The difference is caused by dependence of the local electric field strength on the gap length there. Figure 4b shows the dependence of E-field of the 20-nA emission onset on the gap length at the edge of radii 20 and 50 μm taken into account in calculations of E-fields. It is seen that E_{20nA}

is independent on gap, and choose of edge radius causes just a shift of the line. Thus, the result proves the fact that prebreakdown current depends on the cathode electric field strength only and doesn't depend on total voltage at conditions under the experimentation.

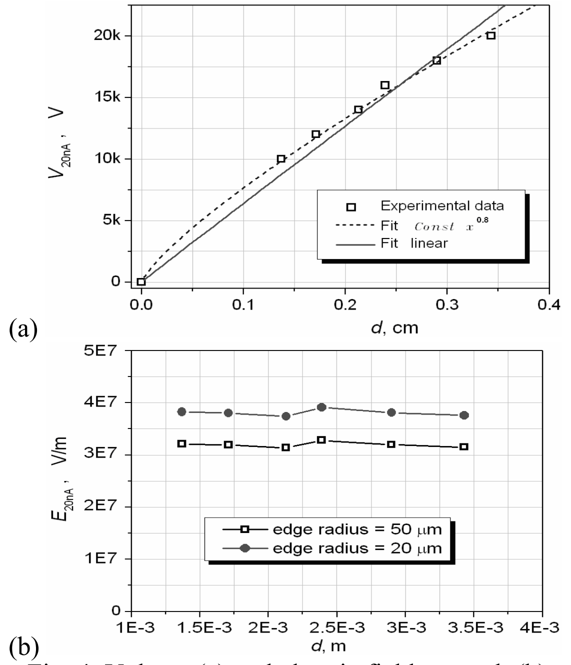

Fig. 4. Voltage (a) and electric field strength (b) *vs.* gap length, at which prebreakdown current is set to 20 nA

3.2 Influence of E-field Rise Rate on Prebreakdown Current

The pulsed regime of prebreakdown current acquisition at dc voltage under scan is caused by moving of an emission site over the needle anode. Such a regime makes it possible to produce pulsed E-field at an emission site. Pulse length could be varied with rotation rate under scan. This allows controlling E-field rise rate with variation of rotation rate. This approach was used in the experimental run on measuring prebreakdown currents at different E-field rise rates. The experimental run consisted of experiments with a needle (on the left in Fig. 2), an artificial MIV site (on the right in Fig. 2), non-treated electrodes made from 321 S stainless steel foil, and EBEST treated electrodes made from 321 S stainless steel foil. Either voltage-current characteristics or E_{on} were measured at the same conditions except of rotation rate that was varied.

Voltage-current characteristics for a needle are shown in Fig. 5. Emission current was rather stable from turn to turn and free of hysteresis. Emission activity of the site appeared to rise with increase of rotation rate.

Much stronger dependence was recognized in the experiment with an artificial MIV site. Emission current from the site was too unstable and demonstrated hysteresis. This is a reason why only dependence of E_{on} on rotation rate was measured for the site (Fig. 6).

Rotation-rate-dependent prebreakdown emission was recognized in the experiment on non-treated plane cathode made from stainless steel foil. A typical example of voltage-current characteristics of the same emission site and different rotation rates is shown in Fig. 7. Behavior of the current-voltage characteristic at rotation rate of 1.4 Hz is shown with arrows.

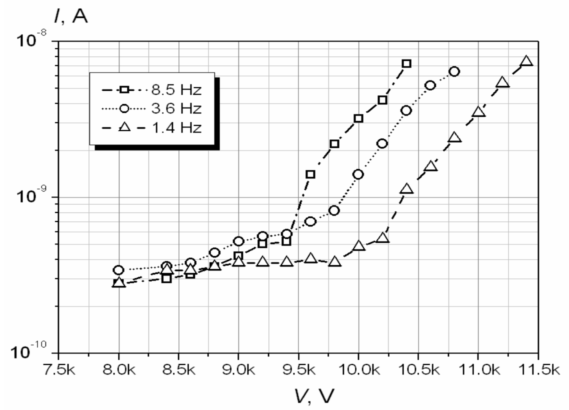

Fig. 5. Voltage-current characteristics of a needle at different rotation rates

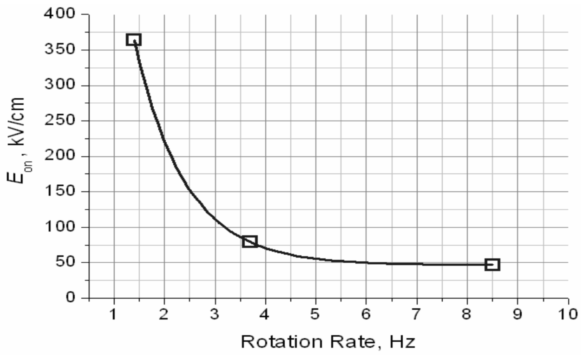

Fig. 6. Dependence of the emission onset E-field on the cathode rotation rate for an artificial MIV site

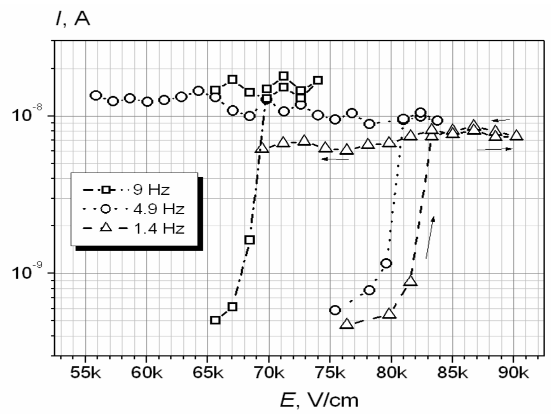

Fig. 7. Voltage-current characteristics of the same emission site at non-treated cathode, at different cathode rotation rates

The common feature of all three experiments is the reduction of threshold voltages with increase of the cathode rotation rate. This would be associated with dependence of prebreakdown current on E-field rise rate unless repetition mode of data acquisition. High voltage affects an emission site from turn to turn, causing probably a cumulative effect. Tentatively, the repetition mode of E-field application can cause accumulation of charge in dielectrics. This produces microscopic-scaled electric fields affecting emission current. Obviously, the shorter is the period between E-field pulses, the more charge remains for the next turn, and higher strength of micro-scaled E-field causes more essential lowering of prebreakdown emission threshold.

Validity of above concept is proved by experiments with EBEST electrodes[2]. It appeared that prebreakdown emission from a clean surface doesn't depend on the cathode rotation rate. EBEST electrode surface doesn't contain big enough dielectric inclusion that could cause the dependence at rotation rates under experimentation.

3.3 Influence of Anode Heating on DC Hold-off

Gas sorption/desorption processes are always considered to assist prebreakdown emission and breakdowns [6]. To value significance of those processes in conditions under the experimentation, experiments with yellow-hot (above 1000 C) anode were carried out. Breakdown electric fields at dc voltages were recoded at emission sites and elsewhere far from them as well, under rotation of a plane cathode. Results are listed in Table 2. Strong positive influence of anode heating on hold-off was recognized.

Table 2. Breakdown electric fields at dc voltages at narrow gaps

ID	Description	dc E_{br}, MV/cm
O_S	At emission sites on cathodes, reference data	0.55±0.03
O_F	Far from emission sites on cathodes, reference data	0.79±0.06
H_S	At emission sites on cathodes at hot anode	1.06±0.09
H_F	Far from emission sites on cathodes at hot anode	2.13±0.2

The orange-hot anode probe (about 800 C) gave the same hold-off level. However, the heating below red-hot threshold doesn't improve hold-off level. Those data meet the idea that anode gas desorption plays a key role in dc breakdown initiation.

3.4 Influence of Anode Heating on Pulsed Hold-off

The results are presented in Table 3 (reference data are available in Fig. 10 of [1]). Electrode heating affects vacuum insulation rather slightly except for the HC_P protocol. The profound fall of hold-off in the case of mechanically polished and red-hot cathodes is probably caused by enrichment of the surface with impurities diffusing from bulk to the surface due to high temperature [7]. Experiments with EBEST and red-hot electrodes demonstrated advantages of electron-beam treatment in improvement of vacuum insulation. Breakdown electric fields were at almost the same level with heating EBEST anodes (CH_E protocol). A detectable rise in hold-off was noted with heating EBEST cathodes (CH_E protocol). It points to the fact that EBEST removes impurities from surface layers essentially deeper than the layer of solidified melt, which correlates well with results of experiments on breakdown of short gaps with EBEST electrodes [8]. The thick layer cleaned of impurities forms a reliable barrier for diffusion of impurities from bulk material.

Table 3. Results of breakdown tests on gaps with electrodes at different temperatures

ID	Description	E_{br}^{1}, MV/cm	E_{br}^{max}, MV/cm
CC_P	Mechanically polished electrodes, cold cathode and cold anode	0.68 ± 0.1	0.77 ± 0.1
CH_P	Mechanically polished electrodes, cold cathode and red-hot anode	0.68 ± 0.07	0.69 ± 0.06
HC_P	Mechanically polished electrodes, red-hot cathode and cold anode	E_{br} < 0.4*	
CC_E	EBEST electrodes, cold cathode and cold anode	0.92 ± 0.09	0.97 ± 0.07
CH_E	EBEST electrodes, cold cathode and red-hot anode	0.96 ± 0.01	0.96 ± 0.01
HC_E	EBEST electrodes, red-hot cathode and cold anode	0.9 ± 0.06	1.09 ± 0.07

***)** Low test E-fields are limited by available space for gap separation.

4. Conclusion

We have recognized different behavior of emission activity at vacuum insulation in respect to the total voltage effect. Hold-off at pulsed voltages does meet TVE while prebreakdown emission at dc voltages doesn't unlike data available elsewhere [3,4,5]. Besides, exact antipodes of behavior at dc and pulsed voltages would meet the Cranberg's model [9] on particle induced breakdown. Our results would look paradoxical unless speculations as follows.

It seems that hold-off is equal to a certain level, E_0, and doesn't depend on d until d is shorter than some threshold length, d_{th}. Hold-off starts to fall as $d^{-1/2}$ with further increase of gap length (Fig. 8). Noticeable fact is that cathode-located prebreakdown emission sites correlate with breakdown events in locations and E-field strength values in the condition of $d < d_{th}$ [1].

[2] Please see voltage-current characteristics of sites 1_1 and 5_1 in Table 1. Beside, the rest of sites were checked on the matter without recording characteristics.

Correlations disappear at $d \geq d_{th}$. Enhancement of electrode surface cleanness increases E_0 only, and this shifts d_{th} to shorter gaps automatically, while $E_{br} \propto d^{-1/2}$ dependence holds the same place. Contrary, contamination of either a cathode, or an anode, or both electrodes lowers breakdown fields at $d < d_{th}$ whilst $E_{br} \propto d^{-1/2}$ dependence holds the same place again, and d_{th} becomes longer [2]. Those data prove that the breakdown mechanism based on electrode condition implies both electrodes to be responsible on hold-off level, and emission sites determine location of breakdown events.

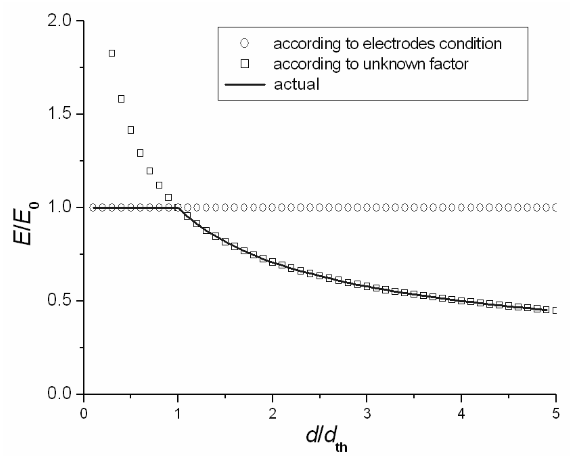

Fig. 8. Schematic presentation of dependence of E_{br} on d

Rejecting possible exotic factors, any experiment on hold-off measurements involves two gaps that are the electrode-to-electrode gap, further referred to as the "test gap", and the electrodes-to-wall gap, further referred to as the "wall gap". All our efforts up to present were targeted on investigation and modification of the test gap while the wall gap is ignored absolutely. However, the wall gap is an unlimited source of contaminants. Inner surfaces of a vacuum chamber are rather rough and covered with loosely bound particles. Certainly, there is no confidence that wall-born particles have no way to get the test gap during pulsed-voltage conditioning before a first-breakdown shot. Herewith, there is no importance of the pulse length. A particle could be detached by a voltage pulse and get the test gap beyond the pulse end. Such an event would produce an emission site. Such a site could initiate a breakdown event with a next voltage pulse. There is no base to consider wall-born particles as a cause of TVE manifestation at short-pulsed voltages. However, those particles could be a cause of sluggishness in improvement of vacuum insulation. In particular the concept of wall-born particle could probably explain the failure of gap treatment with the electrostatic catcher in this work.

It was demonstrated also with red-hot electrodes that gas desorption doesn't play a significant role in breakdown initiation at pulse length of about 100 ns. That is why this factor can't be considered as a cause of TVE manifestation at short-pulsed voltages. On the contrary, the strong dependence of hold-off on anode temperature was recognized at dc voltages.

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