Influence of Cathode and Anode Surface Contaminants on Pulsed Electrical Breakdown of Broad-Area Gaps in Vacuum[1]

A.V. Batrakov, D.J. Johnson*, S.A. Onischenko, and D.I. Proskurovsky

Institute of High Current Electronics SD RAS, 2/3, Akademichesky Ave., Tomsk 634055, Russia,
http://avbatr.fromru.com/
** Sandia National Laboratories, Albuquerque, New Mexico 87115, USA*

Abstract – The cathode phenomena are considered as a rule to be responsible in the first place on any electrical breakdown in vacuum while anode mechanisms play rather an auxiliary role. To check this statement for the case of broad-area vacuum gaps, the special experimental run was performed. Experiments were performed in high oil-free vacuum. Plane electrodes had Chang profiled edges providing uniformity of electric field in a plane-parallel gap. Loosely bound dust particles were used as intentional surface contaminants. To minimize intrinsic surface contamination, the electrode surfaces were preliminary irradiated by pulsed electron beam in the mode of melting a thin surface layer. Four situations were statistically checked in breakdown experiments, which are (i) clean cathode and clean anode, (ii) clean cathode and dusty anode, (iii) dusty cathode and clean anode, and (iv) dusty cathode and dusty anode. Experiments were performed with using various pulse durations. The results obtained are analyzed in terms of the dust particle mechanism of breakdown initiation.

1. Introduction

An interest in study of electrical breakdown in vacuum is fed by numerous advantages of vacuum insulation with reference to many pulse power applications. Herewith, nanosecond range of pulse duration meets the most of cases. At nanosecond pulsed voltages, a cathode of a gap is considered to be basically responsible on breakdown initiation [1, 2] since light emission of plasma starts at a cathode in the first place [2]. Up to now, this fact continues to define the search for mechanisms of breakdown initiation at short-pulse voltages in direction of cathode phenomena. That is why the study of the role of an anode in pulsed vacuum breakdown is featured with the absence of comprehensiveness, though there are investigations pointing out the importance of anode mechanisms in initiation of vacuum breakdown [1, 3, 4].

Either cathode or anode mechanisms of electrical breakdown in vacuum pay especial attention on cleanness of corresponding electrodes. This gives a ground to use the surface cleanness as litmus for detection which mechanism is more responsible on breakdown at certain conditions. So, this work takes aim to check separate influence of cathode and anode cleanness on electric strength of vacuum insulation at nanosecond range of pulse duration. The intentional contamination was used to provide identical conditions of electrode surfaces. Various pulse durations allowed more certainty in experimental results analysis.

2. Techniques and Methods

A. Experimental conditions

All the experiments were performed in conditions of high oil-free vacuum (10^{-6} mBar or better). A couple of 8-cm-diameter electrodes formed a plane-parallel gap. Manipulations with electrodes and their installation into the chamber were performed in dust-free environment provided by the air-filtering equipment based on HEPA H13 air filters. The use of dust-free clothes and mask and powder-free gloves was obligatory condition in manipulation with electrodes.

B. Breakdown test procedure

On a set-up intended for high voltage tests, which was used at IHCE [5], a quasi-rectangular voltage pulse of amplitude ~230 kV and FWHM either 60 ns or 30 ns, produced by a Marx generator, was applied to a vacuum gap formed by electrodes of diameter 8 cm. The electric field between the electrodes was varied by *in situ* varying the width of the vacuum gap. Tests were started at fields that certainly would not result in breakdown. Then the electrodes were gradually brought closer to each other with step not over 100 μm, and a high voltage pulse was applied to the gap at each step until a first breakdown took place. The following high voltage pulses were applied to the same gap until there occurred a series of five pulses without breakdown. In this case, the electrode separation was decreased by one step and the procedure was repeated. The conditioning of the gap ceased as the breakdown voltage increased to some value as a result of the initiation of a high-current arc. With further conditioning, the arc caused a significant erosion of the electrodes, resulting in a decrease in electric strength.

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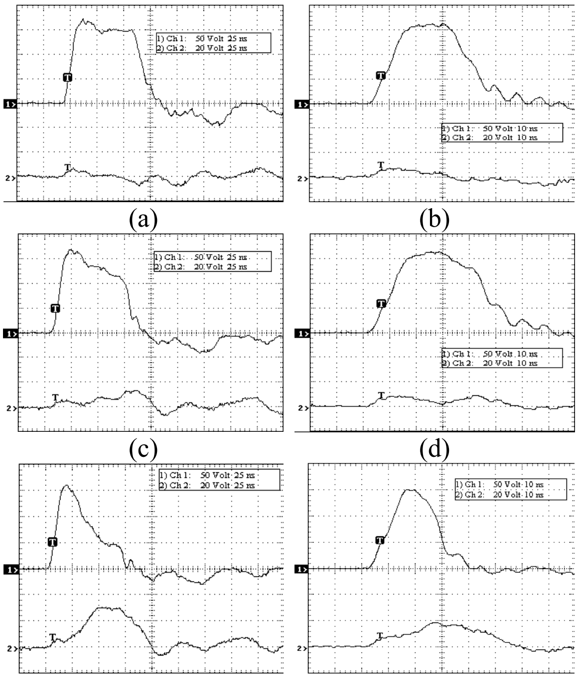
Two criteria of breakdown were used in the experiments. The basic criterion was the registration of a gap current waveform corresponding to discharge. Fig. 1 presents typical waveforms of the gap voltage and the gap current at two different pulse durations. The cathode spot(s) glow was an additional breakdown criterion. The criterion was especially useful in cases of low-current breakdowns.



(a) (b)

(c) (d)

(e) (f)

Fig. 1. Typical waveforms of the gap voltage (upper traces, 75 kV scale) and gap voltage (lower traces, 400 A scale) at longer ((a), (c), and (e); 25 ns scale) and shorter ((b), (d), and (f); 10 ns scale) pulse durations, corresponding to (the up row) absence breakdown and breakdown of (the middle row) lower current and (the bottom row) higher current

C. Electrodes performance and preparation

All the electrodes were shaped as plane cylinders of 8-cm diameter and 1.25-cm thick with Chang-profiled edges to provide the uniform electric filed in a gap. The electrode material was stainless steels 304L. Electrodes were annealed in hydrogen (HVFF). Then, electrodes were treated with using the electron-beam enhancing surface technology (EBEST) [5] in the mode of thin-layer surface melting.

Further handling of electrodes depended on a task. Table 1 lists all the cases for which data are available by the paper writing. We used intentional contaminations of two kinds. The first one is loosely bound dust particles distributed by discharge plasma during EBEST treatment in specialized set-up. These particles can be removed with wiping just before installation of electrodes into breakdown-test set-up. To provide reproducible contamination, we skipped the wiping procedure for certain electrodes.

Intentional contamination with nano-sized (~10 nm) carbon particles was also used. Electrodes were contaminated by means of spraying the certain quantity of ethanol-based suspension containing nano-particles. Each experimental run includes three to five measurements. All the data were compared with results on hold-off for EBEST wiped electrodes made of the same steel, obtained at the same experimental conditions [6].

Table 1. Experimental runs identification and description

ID of experimental run	Electrode preparation	HV pulse FWHM, ns
WKNA	Wiped (clean) cathode and non-wiped anode	60 ± 10
NKWA	Non-wiped cathode and wiped (clean) anode	60 ± 10
NKNA	Non-wiped cathode and non-wiped anode	60 ± 10
CKDA$_{60}$	Clean cathode and dusty anode	60 ± 10
DKCA$_{60}$	Dusty cathode and clean anode	60 ± 10
DKDA$_{60}$	Dusty cathode and dusty anode	60 ± 10
CKDA$_{30}$	Clean cathode and dusty anode	30 ± 5
DKCA$_{30}$	Dusty cathode and clean anode	30 ± 5

3. Results

Figure 2 contains the data on first breakdown electric field, E_{br}^{1}, and maximal breakdown electric field achieved with breakdown conditioning, $E_{\mathrm{br}}^{\max}$, for WKNA, NKWA, and NKNA experimental runs. It is clearly seen that loosely bound contaminants present on both electrode surfaces decrease heavily E_{br}^{1}. Either cathode or anode contaminants present separately deteriorate hold-off in less degree. However, the slightly more negative influence of anode contaminants on E_{br}^{1}, in comparison to cathode ones, was much unexpected.

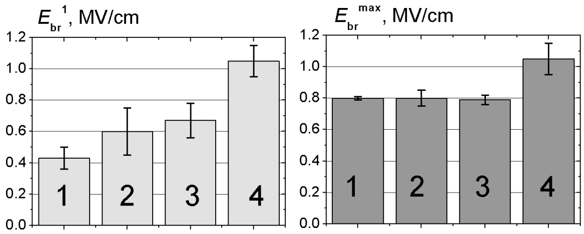


Fig. 2. Breakdown electric fields measured in (1) NKNA, (2) WKNA, (3) NKWA, and (4) reference experiments on clean electrodes [6]

Note breakdown conditioning equalizes breakdown fields of gaps containing one or both dusty electrodes. This is a result of exchange of contaminants between electrodes under breakdowns.

The similar results were obtained in experiments on intentional contamination of electrode surfaces with nano-particles at the same pulse duration (Fig. 3). The only differences are lower breakdown fields and nearly absence of increase in hold-off with electrical conditioning.

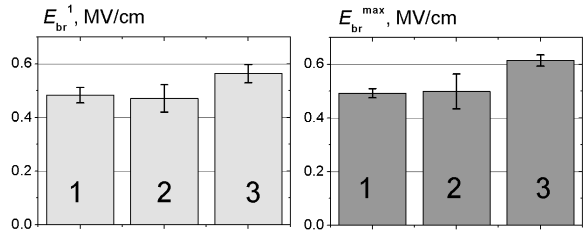


Fig. 3. Breakdown electric fields measured in (1) $DKDA_{60}$, (2) $CKDA_{60}$, and (3) $DKCA_{60}$ experiments

Decrease of pulse duration inversed correlations of breakdown fields. Unlike the longer pulse duration, cathode contaminations worsen vacuum insulation to a greater extent than anode ones (Fig. 4), so, the cathode cleanness becomes most important.

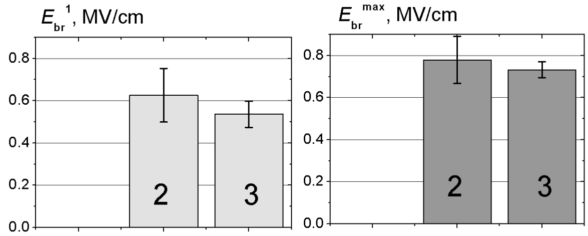


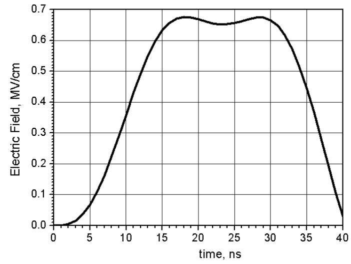
Fig. 4. Breakdown electric fields measured in (2) $CKDA_{30}$ and (3) $DKCA_{30}$ experiments

The inversion in correlations of breakdown fields means a change in the breakdown mechanism with shortened pulse duration. Let us some considerations on this matter.

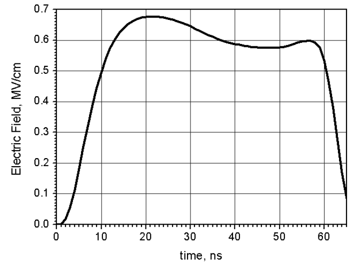
4. Discussions

Analysing the data obtained, we shall take into account the specifics of surface contamination being intentional and representing loosely bound minute particles. That is why the particle launching mechanism [1] of electrical breakdown in vacuum seems to be most suitable one. Herewith, it is supposed that particles start motion at the anode, are accelerated in the gap, and produce plasma at the cathode as a result of impact. The possibility for a nano-particle to initiate a breakdown was shown for the 1 – cos(ωt) voltage pulse of 150 ns FWHM [7]. That approach is applied here for quasi-rectangular voltage pulses closely similar to those used in the experiments (Fig. 5).

A key parameter of the simulation is the M/Q ratio where Q is the number of elementary charges and M the number of nucleons. We did find maximal M/Q values satisfying requirements for a particle to have a time to cross the gap by the end of the pulse flat. Doing this, the gap was assumed to be of 3.5 mm and launching electric field of 500 kV/cm. The results of the simulation are listed in Table 2.



$$E(t)=1.36\times10^{8}\left(\sum_{j=1}^{2}e^{-0.7j^{0.9}}\left(\sin\left[j^{1.005}\frac{\pi t}{57}\right]\right)^{3}\right)$$



$$E(t)=1.5\times10^{8}\left(\sum_{j=1}^{10}e^{-0.7j^{0.9}}\left(\sin\left[j^{1.005}\frac{\pi t}{95}\right]\right)^{3}\right)$$

Fig. 5. Electric field pulses used in the simulation. In the formulas, E is in V/m and t in ns

Table 2. Maximal M/Q ratios and corresponding impact velocities and energies of nano-particles meeting the ratios

Pulse length, ns	30	60
M/Q_{max}	~ 250	~ 1500
v, m/s	4.5×10^{5}	1.5×10^{5}
ε, J (keV)	~ 35×10^{-15} (~220)	~ 35×10^{-15} (~220)

It is seen that a biggest carbon particle having a time to cross the gap at the shorter voltage pulse consists of about twenty atoms. It is much more likely that such a particle too small to produce enough plasma for further discharge self-sustaining, and discharge starts to operate according explosive emission mechanism [2]. Otherwise, longer voltage pulse gives a time for much bigger particles to reach the cathode whilst there exists the gap voltage. Such a particle has lower but still very high velocity. At such velocities, plasma produced in impact is completely ionised [8].

In spite of a high velocity, an M/Q=1500 particle produces rather a minute plasma cloud consisting of about 5×10^{4} heavy particles in a case of an iron surface under impact. At average heavy species concentration of 10^{20} m^{-3}, the plasma cloud radius is of about 10 microns. According to known expression for current, *i*, in a plane-parallel gap with a small emitting hemisphere on the cathode [9]:

$$i = 0.47\sqrt{\frac{e}{m}}\left(\frac{rV}{d}\right)^{\frac{3}{2}}$$

where *e*, *m*, *r*, *V*, and *d* are elementary charge, electron mass, emitter radius, gap voltage, and gap length correspondingly (Gaussian units), the discharge current from a plasma cloud is essentially below the threshold current of discharge self-sustaining which is about 1 A. Nevertheless, the discharge could start to operate in a case of a long enough cumulative plasma jet shot back from a surface under impact, which was computer simulated for impact by cosmic dust particles [10].

The next question we have to answer is about the reason for a particle to have elementary excess charge. Really, a nano-particle can not gain elementary charge electrostatically since its surface is too small. A possible method for a particle on the anode to acquire excess charge is charging due to prebreakdown electron emission from the cathode. A random electron charges a particle positively as a result of secondary emission. Then, a particle takes off the surface and is accelerated by the gap electric field. This approach describes breakdown as an event at which a particle on the anode surface is happened to be opposite a cathode emission site. Furthermore, the approach explains why both electrodes in a gap are required to be clean to provide high hold-off because this manner reduces the probability of such coincidences.

4. Summary

It has been shown experimentally that even at nanosecond range of voltage pulse durations anode contaminations could be more influencing hold-off in comparison with cathode ones. In process of reduction of voltage pulse duration, cathode contaminations become more influencing hold-off.

The results of the experiments can be tentatively explained in terms of nano-particles launched off the anode, accelerated in a gap, and causing breakdown as a result of impact to the cathode surface.

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