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STUDY OF VACUUM INSULATOR FLASHOVER FOR PULSE LENGTHS OF MULTI-MICROSECONDS *

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Abstract

We are studying the flashover of vacuum insulators for applications where high voltage conditioning of the insulator and electrodes is not practical and for pulse lengths on the order of several microseconds. The study is centered about experiments performed with a 100-kV, 10-μs pulsed power system and supported by a combination of theoretical and computational modeling. The base line geometry is a cylindrically symmetric, +45° insulator between flat electrodes. In the experiments, flashovers or breakdowns are localized by operating at field stresses slightly below the level needed for explosive emissions with the base line geometry. The electrodes and/or insulator are then seeded with an emission source, e.g. a tuft of velvet, or a known mechanical defect. Various standard techniques are employed to suppress cathode-originating flashovers/breakdowns. We present the results of our experiments and discuss the capabilities of modeling insulator flashover.

INTRODUCTION

We are attempting to characterize and control a number of different breakdown phenomena that can limit the maximum field stress that can be supported across an insulator/vacuum interface. The production and expansion of plasma on the cathode surface is a critical problem. Whether the plasma expands directly across the electrode gap or across the cathode surface to the insulator, the system will experience a catastrophic voltage collapse. Techniques such as anodizing, polishing, cleaning and/or "conditioning" the cathode surface are used to raise the threshold field for plasma production. The dielectric constant value and insulator angle can be chosen to minimize field enhancement at one triple junction while increasing the enhancement at the other. Experiments [1], [2] have indicated that if flashover from the cathode is successfully suppressed the region at or near the anode triple junction will become the limiting factor.

Our initial experiments characterized plasma generated by small pieces of velvet on the cathode surface. This effort provided development and testing of diagnostics. The data also validated the design of the experiment and early modeling. Testing of insulators with, and without, velvet generated plasma followed. Breakdowns originating at the anode triple junction (ATJ) and from mechanical defects at the cathode triple junction (CTJ) are in progress.

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EXPERIMENT

The test chamber is shown in Figure 1. The grounded cathode is the lower plate with a current transformer around the supporting stalk. The applied voltage is generated by a 500 J, 100 nF Capacitive Discharge Unit (CDU) that incorporates a triggered spark-gap series switch, waveform shaping components, a triggered spark-gap crowbar switch, and a coaxial cable output. A 250 ohm resistor in series with the CDU output is used to limit the maximum current. The pulser rise time is about 200 ns. Normally the crowbar is activated after 5 μs. Spacing between the electrodes is variable. The vacuum is maintained with a cryogenic pump (CTI - Cryo-Torr 8 cold head with a pumping speed for air of 1500 liters/sec. Testing is done at pressures of less than 5 microtorr.

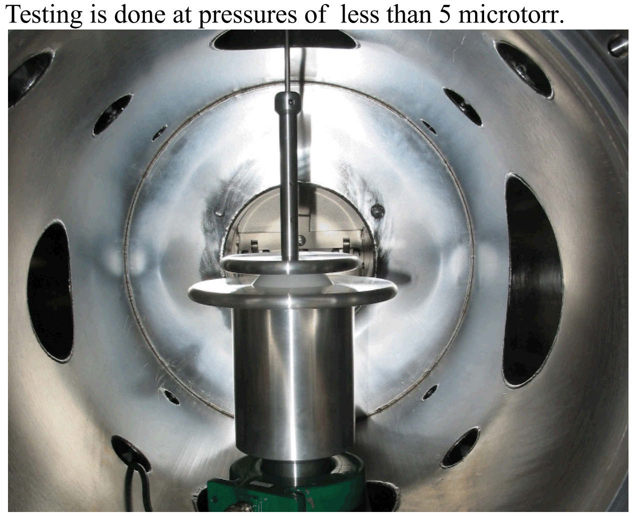

Figure 1: Test chamber with a HD polyethylene insulator installed between electrodes.

Electrodes, Dielectric and Surface Preparation

Electrodes are aluminum with a 32 micro inch finish. For some of the experiments, the cathode is anodized in accordance with MIL-A-8625C to produce a type III (hard), Class-1 (non-dyed) coating with a specified thickness of 0.002 - 0.004 inches. The cathode diameter is 15 cm and the anode diameter is 10 cm.

Two different dielectric materials are used for the insulator: HD Polyethylene and Lexan. The insulators are given a 32 micro inch finish. The Lexan insulator then receives a vapor polishing to produce a clear surface. A transparent surface is important for viewing the "tree" pattern associated with ATJ initiated breakdowns. The insulators are truncated cones with a 45-degree angle and a 6 cm diameter base.

Three different types of velvet have been tested in the experiment. Two were Lucia brands used at the LLNL FXR accelerator for the field emission cathode. However, for our relatively slow rise time, we found that the Double Eagle brand was the most reliable at "lighting off", i.e. formed plasmas at the lowest field stress, and is the velvet used in the results shown below. The velvet is nominally cut with a circular base of 1 mm diameter, a height of about 1.5 mm, and is comprised of about six tufts of fibers. The velvet is then attached to the surface with a small dot of double stick tape (3M, # 465 light industrial, adhesive transfer type). Figure 2 shows a velvet dot positioned near the CTJ of an HD Polyethylene insulator.

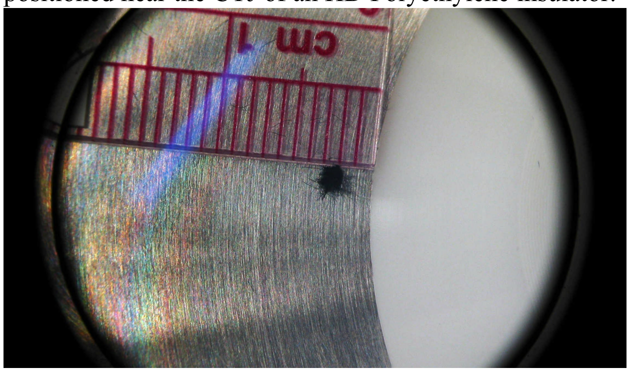

Figure 2. Photograph of velvet dot adjacent to insulator.

Diagnostics

A liquid voltage resistive divider (VRD) attached to the drive cable at the entrance to the vacuum chamber monitors the output of the CDU. The VRD was locally fabricated and calibrated in situ against a commercial voltage probe. The current is measured with a Pearson 110 current transformer installed around the cathode support stalk. Both of these monitors are relatively slow (~20 MHz bandwidth), although sufficient for the plasma studies. We will be installing D-dot probes with sub-nanosecond response, basically terminated coax cables, in the cathode under the insulator. We are also fabricating an anode that will consist of a thin foil of aluminum backed by a scintillating plastic (BC422). The back of the anode will be imaged with a camera to determine the distribution of electrons striking the anode.

Measurements

The first tests were performed with electrode spacing of 1 cm and without an insulator to determine the threshold of the bare aluminum electrodes and the velvet "light-off". Figure 3 shows typical oscilloscopes traces of the voltage and current signals. With no velvet and bare, clean electrodes we held 100 kV across 1 cm for 5 µs. The first pulse on a newly installed velvet dot would occasionally hold voltage for over 1 µs before "light-off" as demonstrated in Figure 3. On subsequent pulses the "light-off" would usually occur during the rise time for CDU charge voltages as low as 60 kV. At 40 kV charge, the velvet "light-off" was delayed or did not occur.

The displacement current provides a time fiducial for the applied voltage and current pulses. Also, the electron transit time is less than 200 ps for the experiment's configurations, so the velvet "light-off" is determined to within a ns from the onset of current and droop in voltage. Complete voltage collapse occurs at plasma closure permitting an estimate of the plasma velocity. Figure 4 shows plasma velocity based on time of gap closure after plasma initiated emission as a function of voltage. The data with error bars indicate the average values with standard deviations for the three different CDU charge voltages. The different breakdown voltages compared to charge voltage is believed due to the slightly different rise times. There does appear to be a trend for greater plasma velocity with increased voltage and/or electric field.

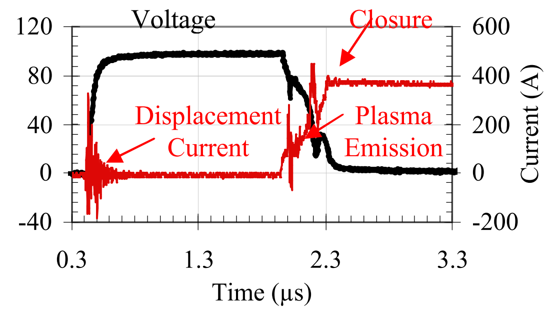

Figure 3. Voltage and current signals for velvet only.

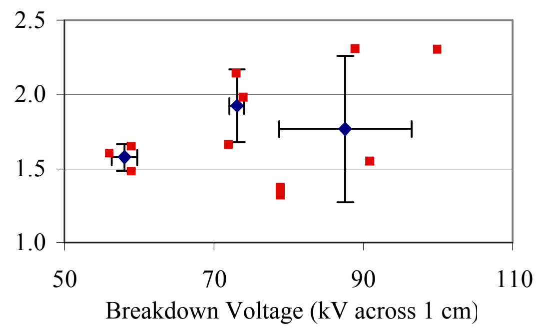

Figure 4. Plasma velocity (cm/µs) versus CDU voltage.

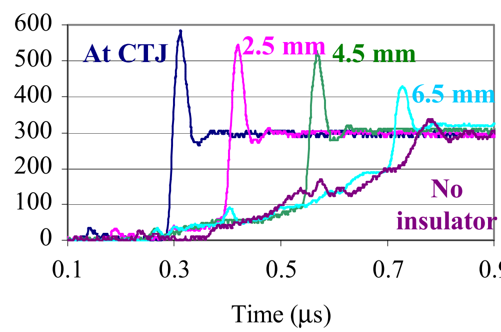

Figure 5. Current signals for velvet at different distances.

A 1 cm thick HD Polyethylene insulator was installed and tested. With no velvet, this arrangement could hold 100 kV. Velvet dots were placed on the cathode at different distances from the insulator to determine the plasma transverse velocity and effect on the insulator. Figure 5 shows a sample of current signals for different distances of the velvet from the insulator. The signals have been adjusted in time so that the velvet "light-off" is consistent. Figure 6 shows current and voltage signals for the case when the velvet dot is 2.5 mm from the CTJ. When the dot "lights-off" the voltage begins to droop.

Plasma arrival corresponds to insulator flashover and voltage collapse. Figure 7 plots the estimated plasma velocity for the different velvet positions with the velocity for gap closure. All data is for a CDU charge of 80 kV. The error bars indicate uncertainty in the location of the velvet "light-off" over the 1 mm diameter of the velvet dot. Shot to shot repeatability produced larger variation.

The plasma expands approximately hemispherically within the accuracy of our measurements. The data does indicate a slowing of expansion with distance. The most important result was that UV from the plasma did not cause the insulator to flashover prior to plasma arrival.

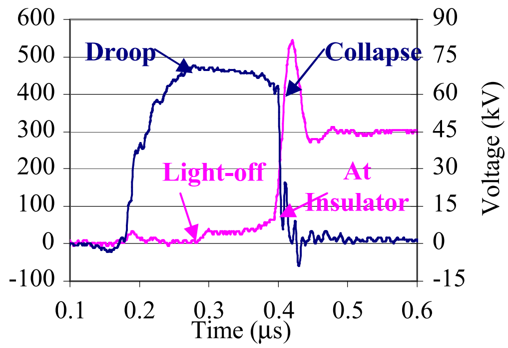

Figure 6. Current and voltage signals for 2.5 mm case.

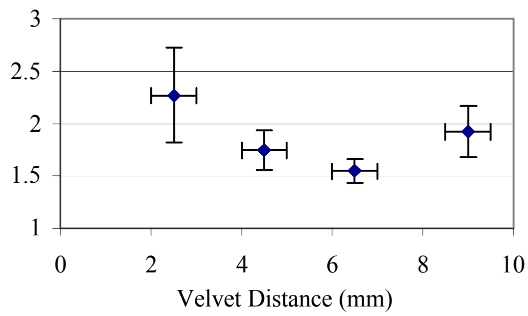

Figure 7. Plasma velocity (cm/µs) for different velvet locations.

Placing velvet on the insulator surface resulted in a delayed (1.6 to 4.8 µs) flashover at 100 kV CDU charge and no flashover at 80 kV charge. When the insulator did flashover, the current/voltage signals were similar to placing the velvet at the CTJ. This response may have a similar cause as the first pulse "light-off" delay noted for the velvet dots on the cathode. In both cases an insulating layer limits the flow of electrons through the velvet fibers. Once the adhesive between the velvet dot and the cathode has been "punctured" this barrier is gone and early "light-offs" can occur, while for the velvet dot on the insulator surface the barrier remains.

A HD Polyethylene insulator was fabricated with a 1.5 mm high step in the base that extended 1.5 cm radially inward from the edge to simulate a condition where the insulator does not sit flushed with the cathode surface. A velvet dot was placed on the cathode in the radial groove about 1.4 cm from the nominal CTJ, i.e. outer diameter of the insulator base. The expectation was that the velvet would "light-off" earlier or at a lower voltage due to the increased field in the gap, the plasma would then expand under the insulator to the CTJ, and the insulator would flashover. The insulator did exhibit a flashover on most pulses with voltage/current signals similar to placing a velvet dot at the CTJ. However, the first pulse on a velvet dot in this configuration had delays before flashover that indicated a much slower plasma velocity than previously measured or a late "light-off". Either occurrence is puzzling and this series of experiments will be continued.

Two configurations were used to study breakdowns originating at the ATJ. Both used anodized cathodes and polished Lexan insulators. The first involved closing the electrode spacing to 3 mm. With no insulator, the 3 mm gap could hold a 80 kV CDU charge. When the CDU charge was increased to 100 kV, there was a plasma formation and gap closure after 4.7 µs. Plasma velocity was about 2.5 cm/µs consistent with measurements for the velvet dots. With the Lexan insulator installed and 80 kV CDU charge, flashovers occurred 0.5, 1.0, and 1.5 µs after voltage application on three sequential tests. The second configuration used a one cm electrode spacing and required a velvet dot at the ATJ for flashover at 100 kV CDU charge. After a slight delay on the first pulse, the flashovers occurred during the rise time of the voltage. There was no indication for either configuration of plasma formation or damage to the anodized cathode surface. However, no damage or "tree" pattern was seen around the ATJ and this study will continue.

THEORETICAL SUPPORT

Field stresses and enhancements due to different hardware geometry were calculated with electrostatic codes for the design of the experiments. Circuit modeling and steady state emission simulations were used to predict diagnostic outputs. We are adding low energy secondary electron emission to LSP [3] for studies of electron avalanches along the insulator surface. Also, a possible mechanism for an ATJ initiated avalanche/flashover is being developed. The goal of the last two efforts is to predict measurable phenomena for the experiments.

ACKNOWLEDGEMENTS

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REFERENCES

[1] G. E. Vogtlin, "Insulator Breakdown Measurements in a Poor Vacuum and Their Interpretation," LLNL, UCRL-JC-103450, June 1990.

[2] W.A. Stygar, et al., "Improved Design of a High-Voltage Vacuum Interface, Phys. Rev. ST Accel. Beams 8050401 (2005)

[3] LSP is a 3-D electromagnetic PIC code used for large scale plasma simulations. The code is licensed by ATK Mission Systems.