UCRL-CONF-212635

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June 1, 2005

IEEE International Pulsed Power Conference
Monterey, CA, United States
June 13, 2005 through June 17, 2005

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Abstract
We have developed a novel insulator concept that involves the use of alternating layers of conductors and insulators with periods less than 1 mm. We have demonstrated that these structures perform 2 to 5 times better than conventional insulators in long pulse, short pulse, and alternating polarity applications. We present new testing results showing exceptional behavior at DC, with gradients in excess of 110kV/cm in vacuum.

I. Introduction
Empirical scaling laws for insulators in a vacuum reveal that the threshold electric field for surface flashover is not directly proportional to the insulator length i.e. doubling the length of a simple, bulk (single material or composite) insulator does not double the voltage where surface flashover occurs.
Literature suggests the most likely mechanism of flashover in a conventional insulator is due to a cascade effect of secondary electrons released from the insulator surface. The High Gradient Insulators (HGI's) developed at LLNL are fabricated using alternating layers of kapton and copper with periods on the order of 0.5mm. We have shown experimentally that these insulators perform significantly better than conventional insulators under a variety of conditions. One theory suggests that the HGI interrupts the process of cascading secondary electrons by placing conductors at periodic intervals along the insulator surface. Thus, the HGI appears to behave as an ensemble of independent insulator structures [1] as shown in figure 1.

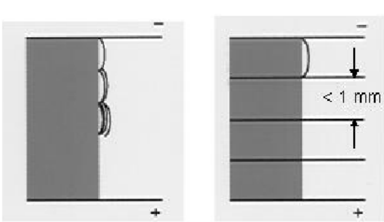

Figure 1

Recent research at other laboratories both in the US and abroad have suggested that the improved performance of this topology is resultant from an alternating gradient formed by the multiple metal/dielectric intervals along the insulator surface [2]. This theory suggests electrons are deflected away from the insulator as a result of the alternating gradient thus inhibiting the production of secondary electrons leading to a cascade failure and insulator flashover. We hope to better understand the exact mechanism(s) involved leading to an HGI surface flashover in order to determine more applicable scaling laws.
Preliminary DC testing of HGI structures in Livermore has demonstrated gradients in excess of 110kV/cm in vacuum, and is pushing the field emission limits of the electrodes. This observed behavior clearly does not follow classical insulator scaling for distance and time [3]. Research continues at LLNL to characterize the performance of this insulator architecture.

II. Testing
Several samples of HGI and bulk insulator material were tested with an applied voltage of up to 170kV DC in vacuum. The test stand and electrode configuration is shown in Figure 2.

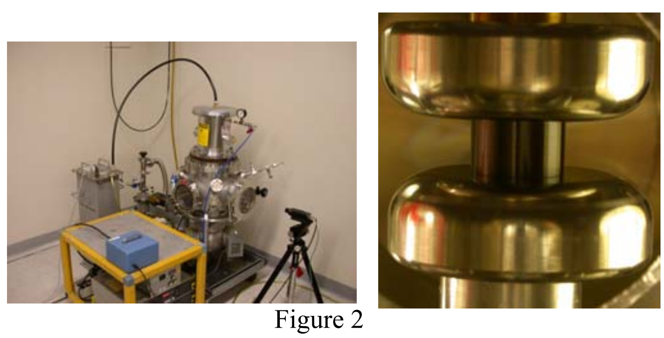
Figure 2

The DC source used was a model 8120 supply from Hipotronics, Inc. This power supply limits fault current to as little as 5uA. Additionally, there is little stored energy in the power supply and interconnect cables, limiting

This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

energy delivered to the test fixture in the event of surface flashover or other fault. As a result, we did not observe damage to the electrodes or the sample insulators following a flashover. For each test, the applied DC voltage was slowly ramped over the course of several minutes. Our diagnostics included the ammeter on the power supply to monitor current, a camera observing the insulator under test to detect flashover, and an ionization chamber type radiation meter.

The electrodes were fabricated out of polished stainless steel. They were first characterized in vacuum (no insulator) by applying a DC voltage with the electrodes spaced 1cm apart. The nominal pressure for all tests performed in the series was $1x10^{-6}$T. Consistent with published empirical data [4], we observed the onset of field emission from the cathode at approximately 120kV. This behavior was characterized by an increase in leakage current and corresponding production of soft x-rays. At slightly higher voltages, we observed a hard arc producing visible light while simultaneously tripping the power supply.

Subsequently, we tested the insulator samples. We observed conditioning behavior consistent with high voltage, low energy systems. For each test, we observed a small number of partial discharges, characterized by a momentary spike in power supply current accompanied by a response from the ionization chamber instrument. A surface flashover was characterized by a visible arc across the insulator and a much larger current spike which would typically trip the power supply.

We tested 2.5cm dia. samples of PEEK, a high-strength organic, Vespel (Kapton), and the HGI insulators fabricated with Kapton and copper. Figure 3 summarizes the test insulators.

Insulator	Partial discharge	Flash-over	Leakage current	Endpoint
1.5cm PEEK	40-50kV	90kV	30uA @ 85kV	repeated flashovers @ 90kV
3cm PEEK	60-95kV	125kV	5uA @ 120kV	repeated flashovers @120-125kV
1.5cm Vespel	20-85kV	120kV	5uA @ 110kV	repeated flashovers @110 – 120kV
3cm Vespel	60-120kV	140kV	3uA @ 140kV	repeated flashovers @140kV
4cm Vespel	95kV	170kV		repeated flashovers @160 – 170kV
1.5cm HGI	70-100kV	90kV		held 170kV for 10 min
3cm HGI	60kV	150kV		held 170kV for 10 min

Figure 3

Some of the samples showed increased leakage current just prior to flashover. This leakage was accompanied by production of soft x-rays on the order of 1 – 10mR/hr at 1m from the test chamber. None of the test samples, including the HGI, appeared to degrade on subsequent trials. The 1.5cm HGI flashed and tripped the power supply at 140kV and 150kV on the first trial, but the hold-off voltage quickly returned to the point of the previous flashover after the power supply was reset. Figure 4 is a plot showing flashover voltage versus insulator length for the test samples.

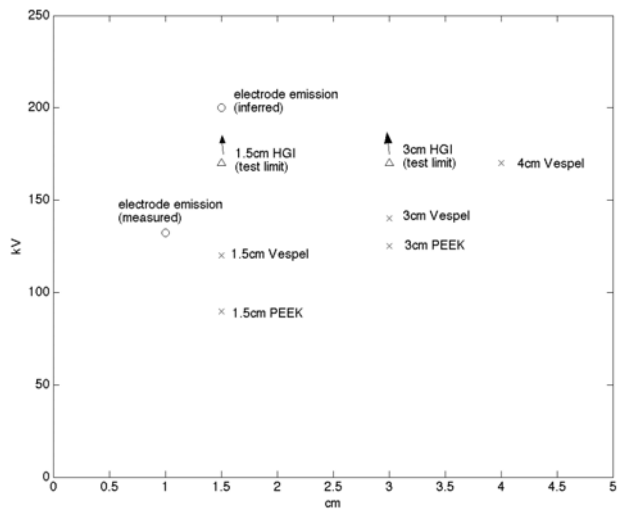

Figure 4

III. Conclusions

The Livermore HGI has demonstrated remarkable behavior at DC. This architecture is attractive for many applications, including portable x-ray systems that require a high gradient DC electric field. Our near-term plans include characterization of the end-point gradient of the HGI. This will require either an HGI sample and more highly polished and/or greened electrodes, or construction of a higher voltage test stand. The conclusions drawn by Leopold, et.al [2] indicate a more optimal spacing of the conductors. We plan to investigate this mechanism further by fabricating and testing high gradient insulators with alternate conductor intervals under pulsed and DC conditions.

IV. References

[1] S. E. Sampayan, et.al. "High Gradient Multilayer Insulator Technology," Proc. 2004 IEEE Power Modulator Conference, San Francisco, CA

[2] J. Leopold, U. Dai, Y. Finkeltstein, E. Weissman and S. Humphries, "Optimizing the performance of flat-surface, high-gradient insulators," IEEE Trans. Dielectrics and Electrical Ins. 12, 530 (2005)

This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

[3] JC Martin, "J. C. Martin on Pulsed Power", edited by T. H. Martin, A. H. Guenther, and M. Kristiansen. Plenum Press, New York, 1996

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