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HIGH GRADIENT MULTILAYER INSULATOR TECHNOLOGY[*]

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Abstract

We are investigating a novel insulator concept that involves the use of alternating layers of conductors and insulators with periods less than 1 mm. These structures perform 1.5 to 4 times better than conventional insulators in long pulse, short pulse, and alternating polarity applications. We have surveyed our ongoing studies by investigating the performance under long pulse electron beam, short pulse, and full reversing conditions.

I. INTRODUCTION

It is experimentally observed that insulators composed of finely spaced alternating layers of dielectric (<1mm) and thin metal sheets have substantially greater vacuum surface flashover capability than insulators made from a single uniform substrate [1]. In our previous work we showed these structures to sustain electric fields 1.5 to 4 times that of a similar conventional single substrate insulator (fig. 1) [2]. We also previously reported on the capability of these structures under various pulse conditions and in the presence of a plasma cathode and electron beam. Further, we have explored the properties of these structures in the context of switching applications, investigating their behavior under high-fluence photon bombardment [3] and the effect on RF modes [4,5].

A high-gradient insulator (HGI) consists of a series of very thin (<1mm) stacked laminations interleaved with conductive planes (fig. 2). This insulator technology was originally conceived and disclosed by Eoin Gray in the early 1980's [6] and resulted from experimental observations that the threshold electric field for surface flashover increases with deceased insulator length [7,8].

Some understanding of the increased breakdown threshold of these structures may be realized from the basic model of surface flashover. A simplified vacuum surface breakdown model suggests that electrons originating from the cathode-insulator junction are responsible for initiating the failure [9]. When these electrons are intercepted by the insulator, additional electrons, based on the secondary emission coefficient of the surface, are liberated. This effect leaves a net positive charge on the insulator surface, attracting more electrons and leading to escalation of the effect or Secondary Electron Emission Avalanche (SEEA) breakdown with full evolution of the discharge requiring approximately 0.5 mm [10].

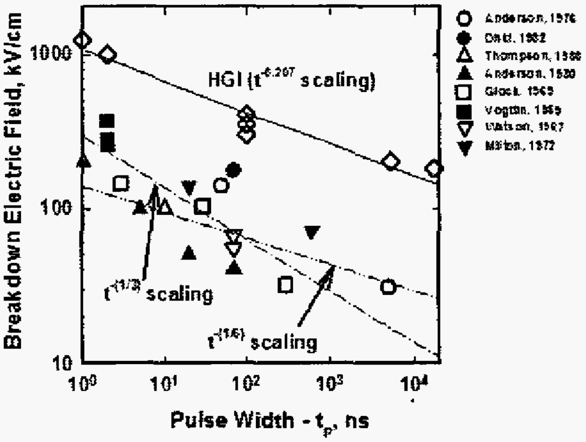

Figure 1. Comparison of the breakdown electric field of conventional single substrate insulators (0°) with the high gradient multilayer insulator (HGI).

More recently, others have concluded that surface flashover results from charge injection into the insulator bulk at an electrode interface and near to the surface [11, 12]. The mechanism consists of three stages: an initiation stage at one electrode, a development stage along the surface just inside the insulator, and a final stage consisting of a discharge in vacuum. This proposed

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mechanism is consistent with the observed growth of prompt high current surface discharges: build up times to full current can occur on the order of 1 ns.

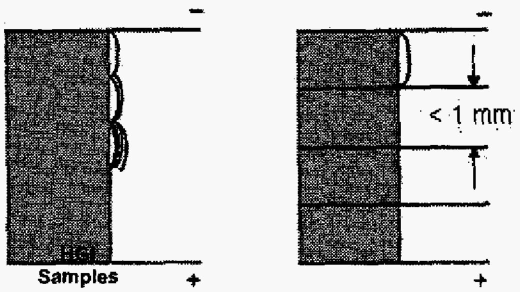

Figure 2. Convention insulator geometry (left) and HGI geometry (right).

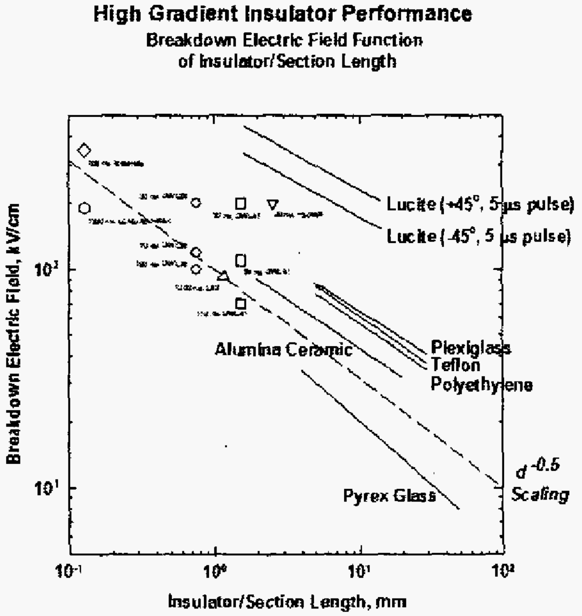

Figure 3. Insulator length scaling effects on the surface breakdown electric field strength. Scaling parameter is overall length for conventional insulators and insulator period for multilayer high gradient insulator.

Both models predict an insulator breakdown scaling of $d^{0.5}$ (where d is the insulator length). Comparison of this scaling for various conventional single substrate insulator materials is shown in figure 3. Also shown on the same plot is the HGI structure but with the scale length of the insulator period. These HGI structures ranged in overall length from 10 to 50 mm. What is observed is that the HGI follows the same general $d^{0.5}$ trend based on the insulator period [12]. Thus it appears that these high gradient multilayer structures behave as an ensemble of independent conventional insulator structures of length d.

II. INSULATOR TESTING

We have performed various testing of these insulator structures under various beam conditions. These tests have included 200 kV/cm, 1 kA short pulse (20 ns) conditions and beam testing on the ETA-II accelerator (nominally 5.5 MeV, 2 kA, 70 ns) near the beam dump. More recently, we have pursued testing for the DARHT II accelerator [13] under long pulse (2 μs) conditions.

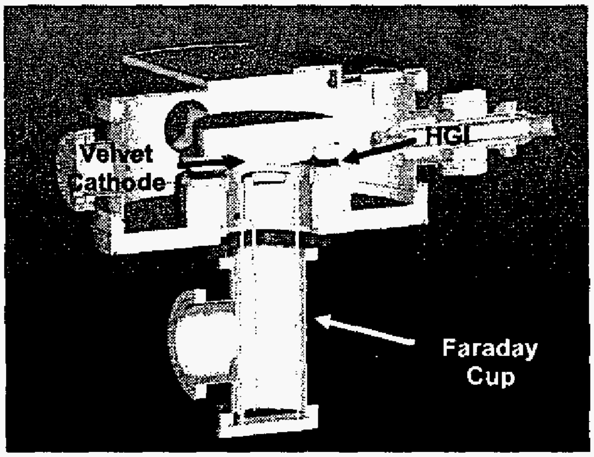

Figure 4. Long pulse electron beam tests of an HGI structure.

These tests (figure 4) demonstrated reliable operation at a field stress of 100 kV/cm in the vicinity of a plasma cathode for a 1.5 cm thick by 28 cm outside diameter structure. To achieve long pulse conditions, the diode A-K gap was extended to 2.5 cm. The resultant current was approximately 0.4 kA for the first microsecond, increasing to a peak current of approximately 0.6 kA for the remainder of the pulse: this latter effect resulting from the advance of the emission boundary toward the anode (fig 5).

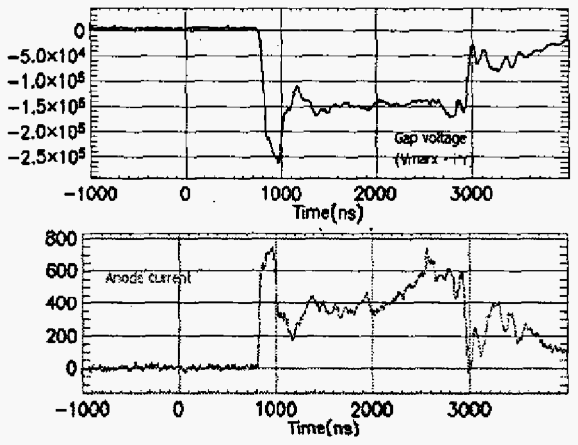

Figure 5. Voltage (top) and current (bottom) during long pulse diode tests.

These structures were further developed into a 3.5 cm x 32.5 cm outside diameter device for eventual testing on the actual DARHT II accelerator under full beam conditions (fig. 6). Initial non-beam tests verified the performance of these structures at greater than 315 kV for 6 μs (FWHM). From our scaling relation developed in figure 1, the expected performance under DARHT II parameters would approach 400 kV for approximately a 2x safety factor under the present baseline accelerator cell requirements.

Figure 6. Full scale DARHT II replacement insulator.

We have also pursued this insulator technology for compact, high gradient accelerators [14]. For this particular application, a short pulse (< 3 ns) is required. To perform this particular set of tests, we implemented a commercial short pulse Marx generator with a peaking gap to our existing small sample insulator test chamber (fig. 7). To accommodate the available voltage from the Marx, only a 3 mm sample was used (fig. 8).

A representative waveform used for these tests is shown in figure 9. In this particular data, the pulse was approximately 1 ns (FWHM). Under these conditions, we were able to achieve >1 MV/cm. We are also exploring the possibility of extending these tests to larger samples to minimize any small sample scaling effects.

The HGI structures have also been subjected to an oscillating pulse. In this test, a Marx generator was allowed to undergo free oscillation with an inductive load. Period of the oscillation was approximately 500 ns. In this test, the HGI performance was compared to a similar conventional insulator structure using the same comparison as in figure 3. These results are shown in figure 10. On this plot, the HGI structure shows a maximum field of 200 kV/cm for a 0.2 mm period. Comparison with conventional large-scale structures (4 and 20 mm period) and a monolithic structure (approximately 18 mm in length) are also shown [15].

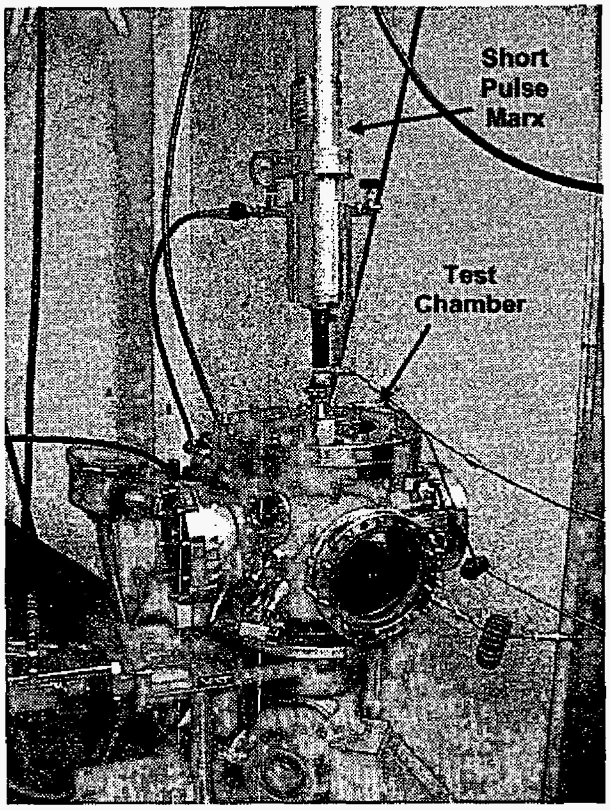

Figure 7. Short pulse testing of the HGI.

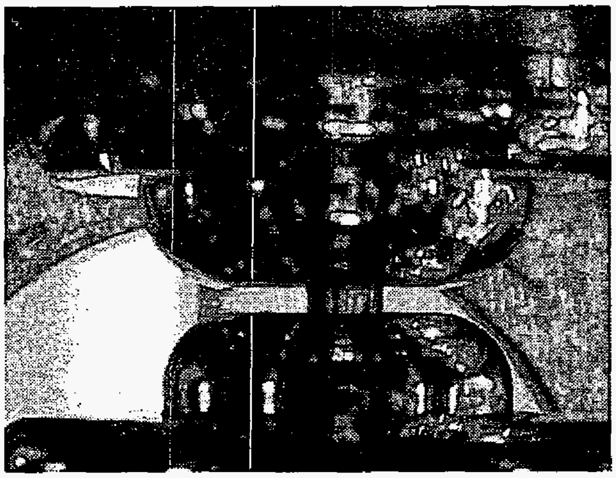

Figure 8. 3 mm HGI sample used for short pulse testing.

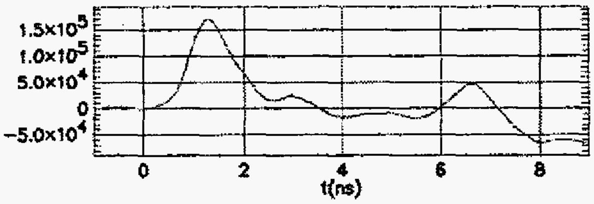

Figure 9. Representative waveform used in the HGI short pulse testing.

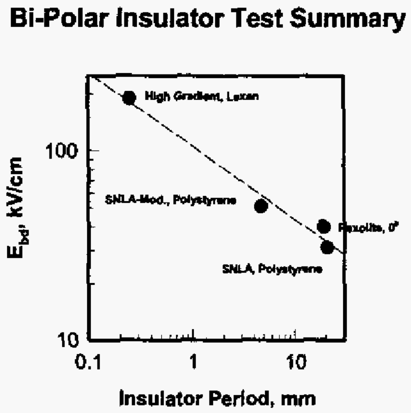

Figure 10. The effect of period length scaling under bipolar stress

III. FUTURE WORK

The increased performance of the multilayer HGI structures has been verified experimentally under a wide variety of conditions. Although the scaling in the performance of these structures appears to be related to the lamination period, the exact mechanism for the improvement has yet to be fully understood. As such, we are initiating systematic studies (both theoretical and experimental) to determine the optimization criteria for these structures.

Additional work is continuing on reliable fabrication of the devices in a production setting to allow more widespread use of the technology. Further, we continue to pursue the work under actual beam conditions with a view to scaling the technology to large-scale systems.

IV. SUMMARY

The HGI appears to behave as an ensemble of independent insulator structures: the scaling quantity is based on the insulator period. Structures with submillimeter periods exhibit 1.5-4x better breakdown strength for 1ns to 20 μs pulses. We have refined techniques to fabricate these structures for consistent results and have demonstrated their performance in actual beam conditions. We have observed short pulse gradients for small samples to be >100 MV/m and the structure is insensitive to reversals.

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