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***Abstract-* Multilayer High-Gradient Insulators are vacuum insulating structures composed of thin, alternating layers of dielectric and metal. They are currently being developed for application to high-current accelerators and related pulsed power systems. This paper describes some of the High-Gradient Insulator research currently being conducted at Lawrence Livermore National Laboratory.**

I. Introduction

High-Gradient Insulators (HGIs) are vacuum insulating structures consisting of thin alternating layers of metal and dielectric. In previous tests, they have been shown to withstand up to four times the gradient of conventional straight-walled insulators without the need for an angled surface [1], and operation up to 100 MV/m has been reported [2]. At Lawrence Livermore, we are studying HGIs as part of our ongoing development of the Dielectric Wall Accelerator, a type of compact, high-current particle accelerator [3, 4]. HGIs are one of three critical technologies for these accelerators, along with high-gradient switches [5] and stacked transmission lines [6]. This paper will describe the two competing theories of operation of HGIs, as well as ongoing HGI research at Lawrence Livermore.

II. Background

HGIs were originally proposed in the 1980s by E. Gray to take advantage of the observation that shorter insulators are generally able to withstand higher gradients [1]. By creating an insulating structure composed of alternating metal and dielectric layers, a large distance can be spanned by what is effectively a large number of very short insulators.

The concept was pursued further by other researchers in the United States [7,8]. These researchers worked under the assumption that the HGI metal layers functioned to physically intercept the secondary electron avalanche generally believed to precede vacuum surface flashover. This assumption led to HGI structures with metal layers which are much thinner than the intervening dielectric (Fig. 1). Metal layers which protrude beyond the HGI surface were also employed, although these were generally difficult to build and maintain [9]. HGIs designed along these lines withstood gradients of up to 40 MV/m for pulse lengths on the order of 100 ns [10], and in one test exceeded 100 MV/m for pulse lengths on the order of 1 ns [2]. This was done without relying on the 45° angle geometry commonly used in conventional high voltage vacuum insulators. In addition, they were shown to function well in the harsh environment found within a high-current particle accelerator [11].

More recently, researchers in Israel and the United States have proposed an alternative method of operation for HGIs. In this model, the metal layers serve to distort the equipotential lines near the HGI surface, producing an alternating electric field directed transversely to the HGI surface (Fig. 2). If the HGI geometry is chosen correctly -- with a half-layer of metal adjacent to the cathode and dielectric layers which are less than three times as thick as the metal layers -- electrons flowing along the HGI surface will receive a net kick away from the surface and the surface flashover will be interrupted [12]. HGIs designed using this model have relatively thick metal layers (Fig. 3).

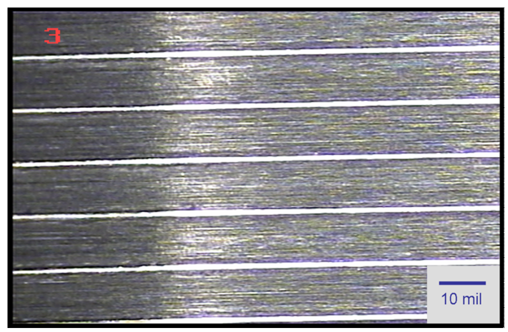

Fig. 1. Surface of an HGI constructed using 10 mil Rexolite layers and 0.5 mil stainless steel layers. Courtesy D. M. Sanders.

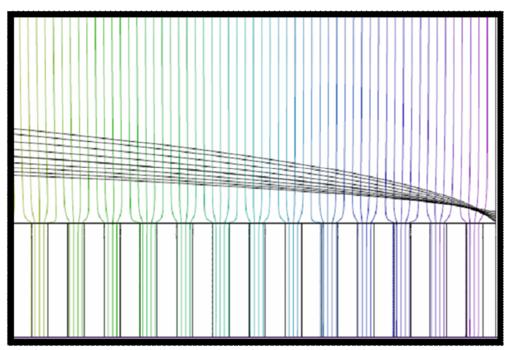

Fig. 2. Deflection of electrons due to bending of equipotential lines near HGI surface (after [12]). Courtesy A.C. Paul.

III. Research at Livermore

HGI research being conducted at Lawrence Livermore is focused on determining how to optimize HGI design for use with Dielectric Wall Accelerators [13].

Toward this end, we have procured a number of small HGI samples for experimental testing. These samples are manufactured by M. Krogh at the University of Missouri-Rolla using Rexolite and stainless steel. They are 2.54 cm in diameter, vary between 2 mm and 30 mm in length, and have insulator-to-metal-thickness ratios between 0.83 and 100. These HGIs are tested under vacuum (2 x 10^{-7} Torr) using a 16-stage Marx generator providing 100 ns FWHM pulses with peak voltages of up to 260 kV and energy up to 16 J. Typical voltage traces with and without surface flashover are shown in Fig. 4, and a typical surface flashover event is shown in Fig. 5. HGI surface flashover events observed to date have all occurred on the leading edge of the Marx pulse, between 5 ns and 20 ns after the onset of the pulse.

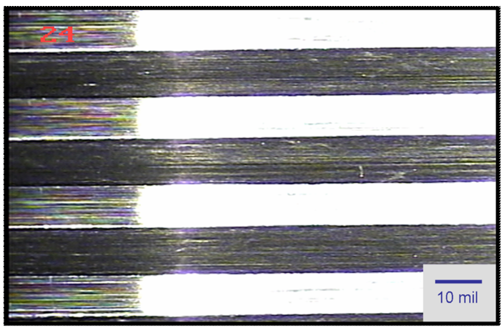

Fig. 3. Surface of an HGI constructed using 10 mil Rexolite layers and 12 mil stainless steel layers. Courtesy D. M. Sanders

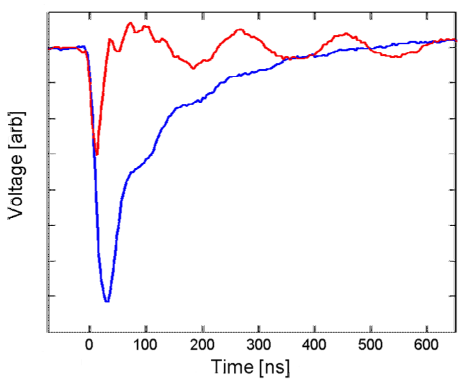

Fig. 4. Typical voltage waveform developed across HGI during normal operation (blue) and HGI surface flashover (red).

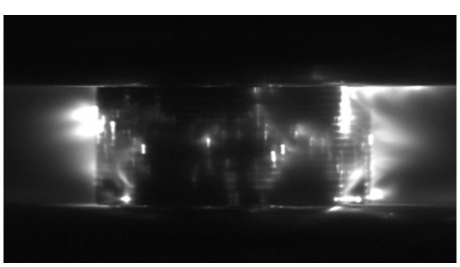

Fig. 5. Typical HGI surface flashover event.

Experiments performed so far have focused on conditionability, as well as the surface damage sustained by HGIs during surface flashover. The Rexolite and stainless steel HGIs tested generally experienced several flashovers at lower gradients (< 10 MV/m) which were accompanied by a relatively large amount of outgassing. These events resulted in some discoloration of the Rexolite, without any apparent adverse effect on HGI operation. These low gradient shots served to condition the HGI, enabling subsequent shots at higher gradient. Higher gradient flashovers were accompanied by the erosion of stainless steel from the metal layers and redeposition of the metal on the Rexolite layers. This was confirmed with energy-dispersive x-ray measurements, and was consistent with photographs of the flashover events. Unlike the discoloration observed at lower gradients, this effect does appear to result in progressive damage to the HGI surface. To evaluate the effect of such progressive damage, one insulator was subjected to 200 shots at nearly full voltage without prior conditioning, and to 23 additional shots at lower voltage. Despite major damage, including serious discoloration and erosion of both the stainless and Rexolite over large portions of the structure surface (Fig. 6), the HGI still held 13 MV/m, which is 64% of its expected, undamaged strength based on previous tests with an identical part. HGIs have not been observed to suddenly suffer a precipitous drop in their strength, as is sometimes seen with conventional insulators. This may be due to the compartmentation effect provided by the intervening metal layers. This robustness bodes well for the use of HGIs in high-power applications.

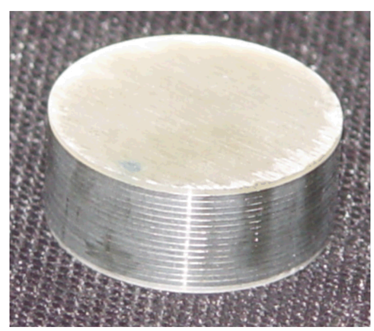

Fig. 6. HGI damage after 223 surface flashover events.

IV. CONCLUSIONS

Research on Multilayer High-Gradient Insulators is ongoing at Lawrence Livermore, in support of Dielectric Wall Accelerator development. HGIs show great promise for use in future high-voltage, compact systems. Tests indicate that they are capable of operating under difficult conditions, and that they are resistant to damage incurred during surface flashover events. Future work will focus on further optimizing HGIs for use in accelerator and pulsed power systems.

ACKNOWLEDGMENT

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