SECONDARY ELECTRON TRAJECTORIES IN HIGH-GRADIENT VACUUM INSULATORS WITH FAST HIGH-VOLTAGE PULSES*

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Abstract

Vacuum insulators composed of alternating layers of metal and dielectric, known as high-gradient insulators (HGIs), have been shown to withstand higher electric fields than conventional insulators. Primary or secondary electrons (emitted from the insulator surface) can be deflected by magnetic fields from external sources, the high-current electron beam, the conduction current in the transmission line, or the displacement current in the insulator. These electrons are deflected either toward or away from the insulator surface and this affects the performance of the vacuum insulator. This paper shows the effects of displacement current from short voltage pulses on the performance of high gradient insulators.

INTRODUCTION

Generally, vacuum insulator failure is due to surface flashover, initiated by electrons emitted from a triple junction. These electrons strike the insulator surface thus producing secondary electrons, and can lead to a subsequent electron cascade along the surface. The displacement current in the insulator can deflect electrons either toward or away from the insulator surface, and affects the performance of the vacuum insulator when the insulator is subjected to a fast high-voltage pulse [1].

Vacuum insulators composed of alternating layers of metal and dielectric, known as high-gradient insulators (HGIs), have been shown to withstand higher electric fields than conventional insulators [2]. HGIs, being tolerant of the direct view of high-current electron [3] and ion [4] beams, and having desirable RF properties for accelerators [5], are a key enabling technology for the dielectric-wall accelerators (DWA) being developed at Lawrence Livermore National Laboratory (LLNL) [6]. Characteristically, insulator surface breakdown thresholds go up as the applied voltage pulse width decreases. To attain the highest accelerating gradient in the DWA, short accelerating voltage pulses are only applied locally, along the HGI accelerator tube, in sync with the charged particle bunch, and the effects of displacement current on trajectories of electrons emitted from HGI surface are particularly interesting. This paper presents simulated electron trajectories experiencing either constant or short-duration applied voltage pulses. Comparisons of these trajectories clearly indicate the importance of the voltage pulse shape, especially the rise time, in the flashover initiation process for HGIs.

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SIMULATION CONFIGURATION

When a DWA is operated in a "virtual" traveling wave mode, a high acceleration voltage pulse is only applied to a small section of the HGI beam tube at any given time. The HGI beam tube is capable of supporting a substantial tangential electric field. To ensure that particles are driven by a high accelerating field comparable to the field gradient on the HGI tube surface, the spatial extent of the electric field on the HGI tube needs to be greater than 1.5 times the HGI tube diameter divided by the Lorentz factor γ [6], which is about 1 for several hundred MeV protons. For a 2-cm inner radius HGI tube, the required axial extent of the voltage excitation on the tube is approximately 6 cm. In our simulations, the HGI is 7 cm in length with an inner radius of 2 cm and outer radius of 3 cm. The axial thicknesses of an individual insulator layer and a conductor layer are both 4 mm. The relative permittivity of the insulator layers is 3.9. Vacuum is assumed both inside and outside the HGI tube.

Although the HGI configuration is azimuthally symmetric, we used LSP [7], a 3-D electromagnetic particle-in-cell code, to study the trajectories of electrons emitted from the HGI surface. The HGI tube is sandwiched between two electrodes. Voltage pulses are applied between these two electrodes from the outer radial boundary. All conducting layers in the HGI are floating. A previous study [8] of steady state electron trajectories in HGIs indicates that to initiate a breakdown, all generation of electrons must occur in the downstream half of a conductor layer or the upstream half of an insulator layer. In the LSP simulations, electrons are born on the surfaces of the first metal-insulator pair (next to the upstream electrode) and the center metal-insulator pair. They are emitted perpendicularly from either the downstream half of the conductor layer or the upstream half of the insulator layer, with an initial energy of 2 eV, and accelerated in the downstream direction (left-to-right in the following figures).

LINEARLY INCREASING VOLTAGE

For comparison, the trajectories of electrons emitted from a bulk insulator with a relative permittivity of 3.9 are also simulated and are shown in Figure 1. The zoom-in view of trajectories near the triple points is given in Fig. 1(b). The dashed red curves are the trajectories when a constant electric field gradient of 60 MV/m is applied. The solid black curves are the trajectories when the electric field is linearly increasing at the rate of 150kV/cm/ns. Figure 2 shows the trajectories of electrons emitted from the HGI. The zoom-in view of the trajectories near the triple points is given in Fig. 2(b). Again, the dashed red curves are the trajectories for a constant 60 M/m gradient, and the solid black curves are the trajectories using a linearly increasing electric field at the rate of 150 kV/cm/ns. These figures show that secondary electrons emitted from the bulk insulator stay very close to the insulator surface while the HGI's multiple metal-insulator layer configuration bends the electric field lines near the HGI surface thereby deflecting the electrons away from HGI [8] on both the inner and outer surfaces. As reported in Ref. [1] and shown in Figure 1, the magnetic field of the displacement current in the insulator deflects the electrons born on the outer surface of an insulator toward the insulator quickly while it deflects the electrons away from the inner surface as the electric field is increased. Figure 2 shows that secondary electrons also experience similar displacement current effects. However, upon comparing the trajectories for the solid dielectric and the HGI shown in Fig. 1 and 2, respectively, we expect the HGI to perform better electrically during the rising part of high voltage pulse.

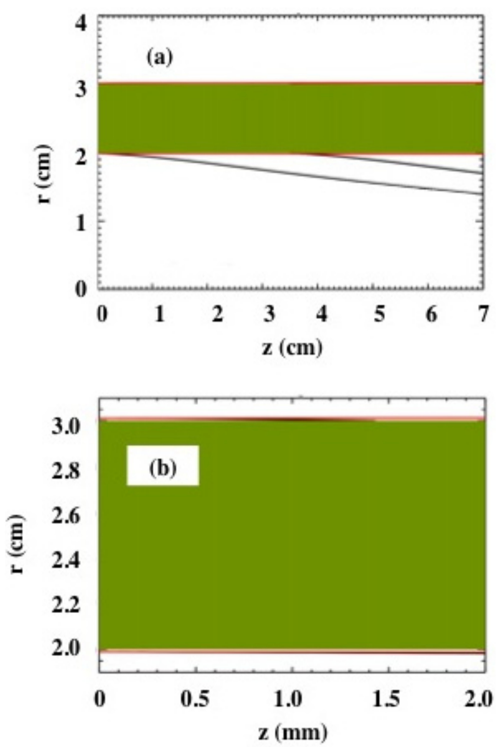

Figure 1: Trajectories of electrons emitted from the surfaces of solid dielectric, with the zoom-in view near the triple point given in (b). The average E_z field is 60MV/m, the electric field ramp rate is 0 (dashed) and 150kV/cm/ns (black).

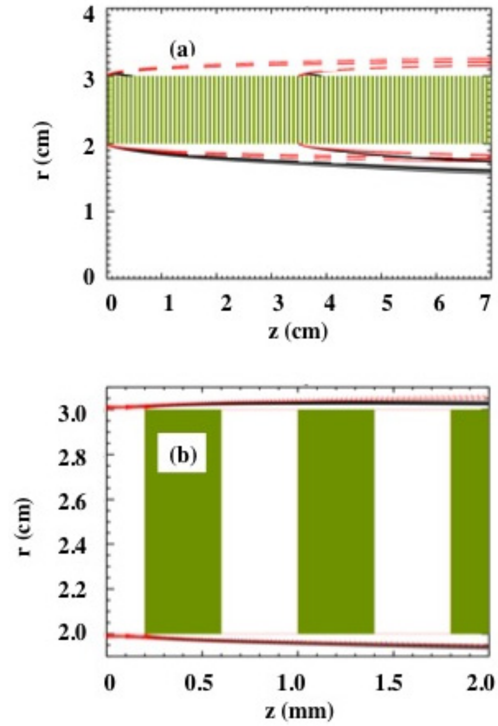

Figure 2: Trajectories of electrons emitted from the HGI with the zoom-in view near the triple point given in (b). The average E_z field is 60 MV/m, the electric field ramp rate is 0 (dashed) and 150 kV/cm/ns (black).

SHORT VOLTAGE PULSES

To study the performance of HGIs for short pulse applications, we calculated electron trajectories when various fast voltage pulses were applied to the HGI. Two of those cases are presented in this paper: a 1-ns FWHM Gaussian pulse; and a 4-ns FWHM pulse with a 3-ns flattop.

The fast 1-ns FWHM voltage pulsed used in the simulation and the resulting electron trajectories are shown in Figure 3. The peak voltage across the HGI stack is 4.2 MV, which gives an average field gradient of 60 MV/m on the HGI surface. Secondary electrons are emitted at various times as indicated in Figures 3(b) - (f). At time = 0.8 ns, the electric field stress rate is about 150kV/cm/ns. As expected, the trajectories of electrons emitted at this time are similar to the solid black trajectories shown in Fig. 2(a). Electrons outside the HGI are pulled toward the HGI surface and electrons inside the HGI tube are pushed away from the surface. At time = 1.1ns, electrons are emitted near the peak of the voltage pulse and are subjected to near zero displacement current effects; hence the trajectories shown in Fig. 3(c) are similar to the dashed red trajectories in Fig. 2(a). Electrons both inside and outside the HGI tube are moving away from the surface. Figures 3(d) – 3(f) show that electrons outside the HGI tube are deflected away from the tube as the voltage pulse decreases. During this time, electrons inside the HGI tube are pulled toward the

HGI surface. However, upon comparing the deflection experienced by the outside electrons during the increasing part of the pulse, with the pulling on the inside electrons during the decreasing part of the pulse, the figures show that the pulling is much weaker.

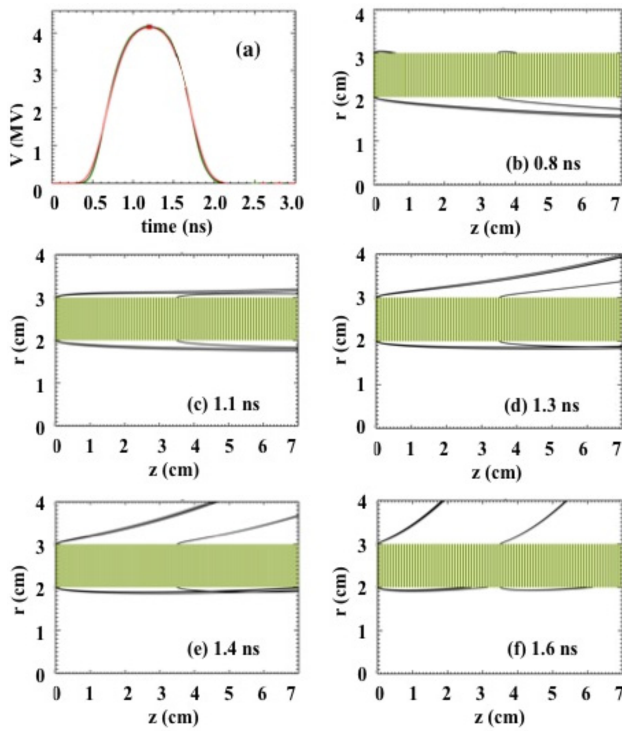

Figure 3: (a) The 1-ns FWHM Gaussian voltage pulse and Trajectories of electrons emitted from the HGI surfaces at (b) 0.8 ns, (c) 1.1 ns, (d) 1.3 ns, (e) 1.4 ns and (f) 1.6 ns.

Comparison of these trajectories indicates that flashover is most likely to be initiated on the outer surface of the HGI tube during the increasing part of the pulse. These simulations indicate that simple right-circular-cylinder HGI samples, instead of HGI tubes, are adequate for testing HGIs' electrical strength when fast voltage pulses are used for testing.

The 4-ns FWHM voltage pulse with a 3-ns flattop used in the simulation and the corresponding electron trajectories are presented in Figure 4. For ease of comparison, the rising and falling sections of the pulse are the same as that of the 1-ns FWHM Gaussian pulse. The peak voltage and average field stress is again 4.2 MV and 60 MV/m, respectively. A comparison between Figures 2, 3 and 4 indicates that the electron trajectories are mainly determined by the electric field's rate of change at the time electrons are emitted.

SUMMARY

We have studied deflection of trajectories of electrons emitted from the HGI surface due to the displacement current in the insulator layers while the HGI is subjected to a fast voltage pulse. Comparison of these trajectory deflections clearly indicates the importance of the voltage pulse shape, especially the rise time, in the flashover initiation process for HGIs.

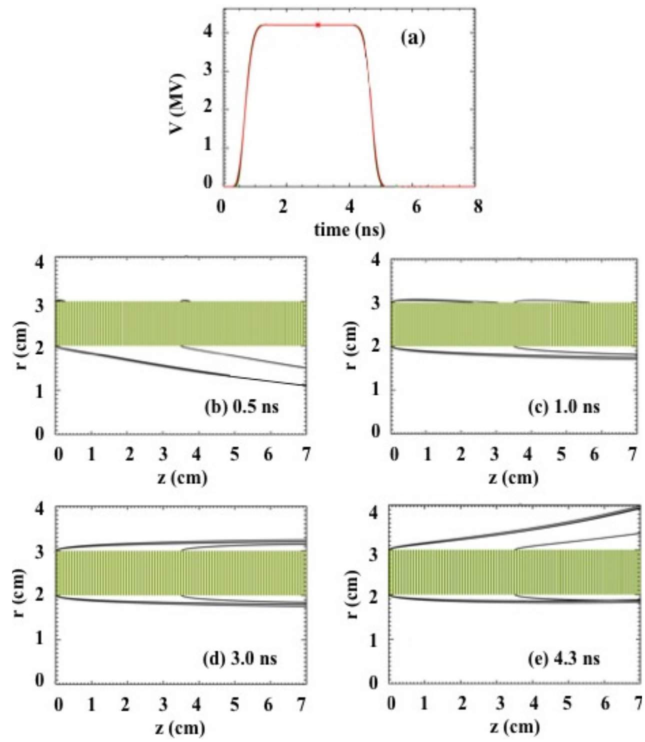

Figure 4: (a) The 4-ns FWHM Gaussian voltage pulse with 3-ns flattop and Trajectories of electrons emitted from the HGI surfaces at (b) 0.5 ns, (c) 1.0 ns, (d) 3.0 ns, and (e) 4.3 ns.

REFERENCES

[1] J. R. Harris, et. al., Appl. Phys. Lett. 91, p. 121504 (2007).
[2] S. Sampayan, et. al., IEEE Trans. Diel. and Elec. Ins. **7** (3) p. 334 (2000).
[3] G. Caporaso, "New Trends in Induction accelerator Technology", Proceeding of the International Workshop on Recent Progress in Induction Linacs, Tsukuba, Japan, 2003.
[4] G.A. Westenskow, et. al., "A Compact High-Brightness Heavy-Ion Injector", PAC'05, p. 1263 (2005)); http://www.JACoW.org.
[5] T.L. Houck, et. al., "Measured and Theoretical Characterization of the RF Properties of Stacked, High-Gradient Insulator Material", PAC'97, Vancouver, Canada, p. 2627 (1997); http://www.JACoW.org
[6] G. J. Caporaso, Y-J Chen and S. E. Sampayan, "The Dielectric Wall Accelerator", Rev. of Accelerator Science and Technology, vol. 2, p. 253 (2009).
[7] Alliant Techsystems Inc., http://www.lspsuite.com/.
[8] J.G. Leopold, et. al., IEEE Trans. Dielectr. Electr. Insul. Vol. 12, p. 530 (2005).