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Abstract **- The vacuum/dielectric interface of insulators is often the weakest part in high voltage and pulsed power systems. Surface flashover can occur for electric field values much lower than that of bulk breakdown through the material. Although much empirical data and many theories can be found in the literature, there are no models that can be used to optimally design insulators and reliably predict when flashover will occur. In this presentation we will discuss the results of a FDTD-PIC code that is being used to model physics phenomena common to many flashover theories.**

In order to simulate the initiation of vacuum insulator flashover, VORPAL [1] is being used on the Linux clusters at LLNL. In [2] we presented the results for implementing physics modules that included the effects of field distortion due to the dielectric, Fowler-Nordheim field emission, low energy secondary emission, insulator charging, and magnetic fields. We have extended our previous work to include a thin gas layer near the surface of the insulator. Electrons may cause ionization depending on their energies and the collision cross section of the gas. The inclusion of these physics effects leads to a more complete model and better understanding of vacuum insulator flashover.

I. INTRODUCTION

Insulators are critical components for many high voltage and pulsed power systems. Since an arc across the surface of an insulator often occurs at much lower electric fields than bulk breakdown through the material, much research has been performed recently at LLNL on surface flashover [2-6]. Although many useful experiments have been performed on surface flashover over the past half-century, none have resulted in any reliable models/theories that can be used to shape insulators and surrounding electrodes for optimum hold off. There are also no reliable models/theories that can predict when flashover will occur or that include different operating conditions such as U.V., magnetic insulation, background gases, and voltage pulse shape. Unfortunately, it is often difficult or prohibitively expensive to create test stands that replicate the environment that insulators must operate under.

These difficulties have resulted in an LDRD effort at LLNL to create a computational model for surface flashover. Due to advances in multi-physics codes and computing power, this problem can now be investigated computationally. The complex coupled physical process involved during breakdown necessitates a multi-physics code, such as VORPAL, be used to gain further understanding and help guide future flashover experiments.

The results in this paper extend on what was presented in [2] by including a static background gas that can be ionized. We will focus on two geometries, a -30° and a +55° insulator. For simplicity, we will use a slab geometry in which the angled insulator with a dielectric constant of 2.7 is placed between parallel plate electrodes. The simulation domain is periodic in the x-direction and has absorbing boundaries at the two ends. A pulse with an E_y equal to 200 kV/cm is used for excitation and a static B-field subtracts out the B-field of the pulse. A small patch near the cathode triple junction (CTJ) and strip on the insulator surface are allowed to field emit via Fowler-Nordheim. An electron that strikes the insulator or electrodes may produce secondary electrons if its energy is not too high or too low. Some modifications were made to the VORPAL code field emission and secondary electron emission modules for our particular application [2]. It was demonstrated in [2] that VORPAL correctly charges the insulator whether an electron is absorbed (charges negatively) or created via field emission and secondaries (charges positively).

Figures 1 and 2 show the evolution of the electrons with the conditions discussed above for the -30° and +55° insulators. In these simulations there is no gas or ions present and no particles are present on the right hand side of the insulator. The figures show the evolution of the electrons by viewing the geometry from the side as well as the face of the insulator (viewing along the z-axis). They also show E_y and the number of macro-particles in the simulation (which represent the electrons). One can see that for the -30° insulator, electrons are first created via field emission from the cathode due to the enhanced field at the CTJ. They then begin to cascade along the insulator due to secondaries. By comparing the right hand and the left hand sides of the E_y plot, one can see how the insulator surface has charged. It is interesting to compare Fig. 1 to Fig. 8 in [2] to see how changing the incident energy and angle changes the results. For the +55° insulator electrons are first created via field emission from the insulator due to the enhanced fields near the anode triple junction (ATJ). They then propagate down towards the cathode due to field emission. For both cases one can see that saturation is quickly reached and the number of macro-particles in the simulation begins to decrease. This indicates that other effects must be included to simulate flashover, such as gas ionization.

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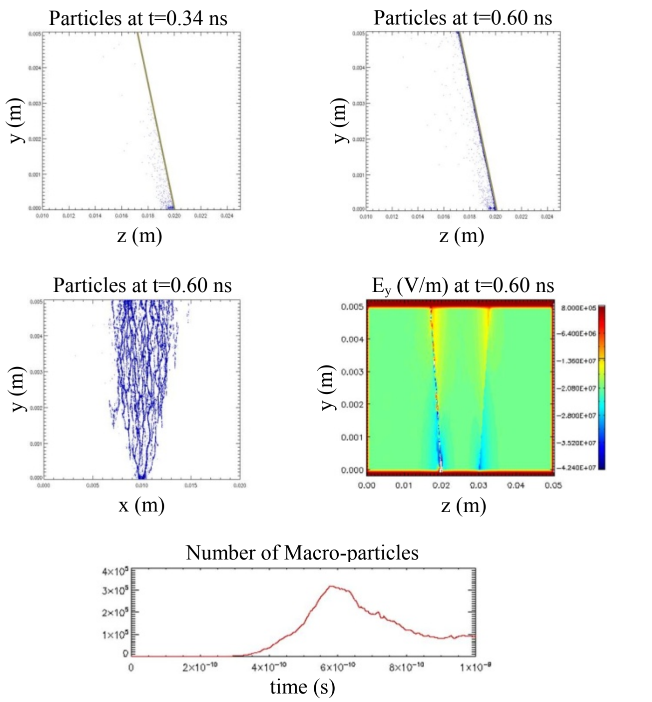

Fig. 1. The electrons and E_y for a -30° insulator with no gas at different times.

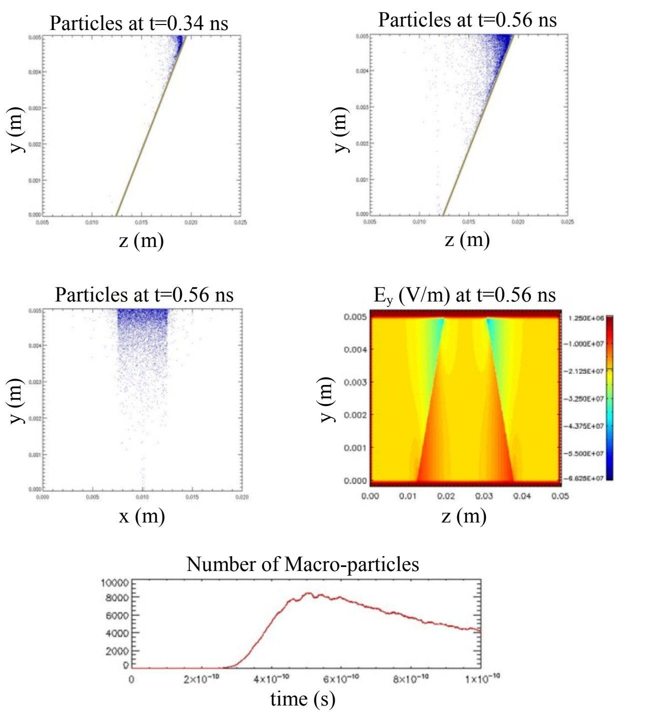

Fig. 2. The electrons and E_y for a 55° insulator with no gas at different times.

II. Electron Collisions With Neutrals

A common hypothesis in flashover theories is that gas desorption from the surface of the electrodes and/or insulator occurs. The gas is then ionized by impacting electrons. Since H_2O coats the surface of electrodes and insulators in many pulsed power systems, it is expected to be the gas of most interest. When electrons strike surfaces electron stimulated desorption and thermal desorption can occur [7]. Due to the ratio of electric field to pressure, ionization of the gas by electron impact is expected to be the most important type of collision [8]. However, other types of collisions can't be neglected because they can scatter electrons towards the surface of the insulator to create secondaries.

Our version of VORPAL includes a static background gas model that can be ionized. Various cross sections of H_2O were found by fitting curves to data in the literature [9, 10] and used in VORPAL. For the ionization cross section, the cross sections of H_2O, as well as its various products (OH, O, …) were added together in an approximation similar to that discussed in [11]. Figure 3 shows the ionization cross section of H_2O and other gases, as well as the results of propagating a 20 eV electron beam through a 2 mm slab of H_2O. The density of H_2O was picked such that half the electrons undergo ionization using $\exp[-\Delta y/n_n*\sigma(20eV)] = 0.5$. By comparing the number of macro-particles for ions to incident electrons we obtain 0.5. Figure 3 exhibits how the electrons are scattered and the direction of the created electrons. One can also see the kinetic energy of the electrons in the beam, the scattered electrons, the created electrons, and the ions.

To adequately include the effects of elastic collisions and other inelastic collisions the VORPAL code was modified. The modifications follow the Monte Carlo technique discussed in Sect. IX of [12]. The type of collision is determined by first normalizing the different collisional processes then using a random number to pick the type. A rough approximation of Eq. (81) in [12] was used to determine the scattering angle for the elastic and inelastic (other than ionization) collisions. An energy of 15 eV was used in Eq. (81) for incident electrons less than 15 eV because the differential cross section of H_2O has a large forward component for low energies. With the added cross sections and the method discussed above, the experiment in Fig. 3 was repeated with results shown in Fig. 4.

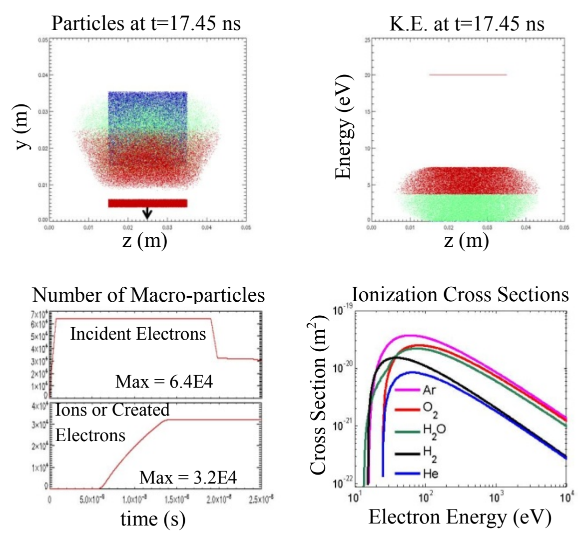

Fig. 3. The effects of an electron beam (red) ionizing a static gas (H_2O), creating "chargeless" ions (blue) and "chargeless" electrons (green), as well as scattering the beam.

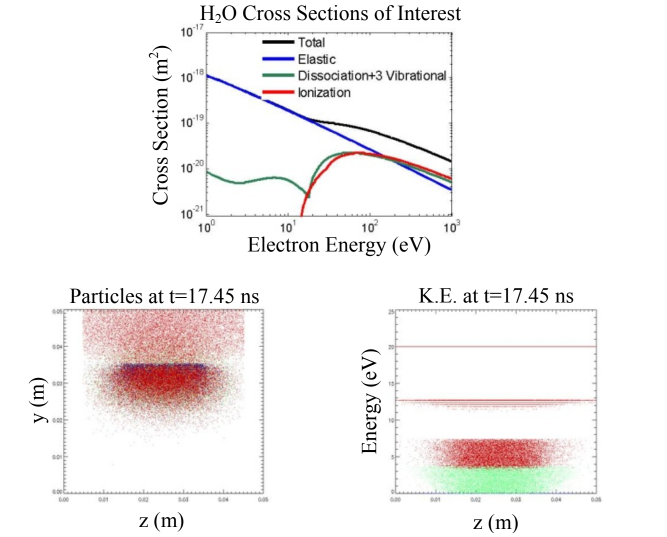

Fig. 4. The effects of including elastic, inilastic, and ionizing collisions for an electron beam (red) colliding with a static gas (H_2O), creating "chargeless" ions (blue) and "chargeless" electrons, as well as scattering the beam.

III. Effects Of Including A Static Gas

Next, we discuss the effects of adding a static background gas that decays as Distance^{-2} from a peak density at the insulator surface to zero over 1.8 mm. First, the simulations shown in Figs. 1 and 2 are repeated using Argon and including only the effects of ionizing collisions. The results are shown in Figs. 5 and 6 for maximum Argon densities of 2×10^{23} m^{-3} and 10^{24} m^{-3}. One can see that in both these simulations the number of macro-particles does not decrease as in Figs. 1 and 2. Next, the angle of the insulator was varied while keeping the maximum background density of Argon equal to 10^{24} m^{3}. The results are shown in Fig. 7. One can see that for positive angles the simulation is producing a result that seems to match the well known experimental curve [13], in which the flashover voltage increases with angle up to approximately 45° then decreases. The hypothesis explaining this behavior is that for a field emission process from the insulator, a gas is created at nearly the same time field emission begins. However, the figure shows that the negative angles do not agree with the experimental curve, which predicts an increase in flashover voltage with decreasing angle to approximately -45° then begins to decrease. This is presumably due to the effect that for negative angles electrons must first strike the insulator to cause gas desorption.

Finally, we have repeated the simulations illustrated in Figs. 5 and 6 using the added cross sections, and modified Monte Carlo collision techniques for H_2O. The maximum density for H_2O was 3×10^{23} m^{-3} and 2×10^{24} m^{-3} for -30° and +55°. The higher densities needed to cause flashover are presumably due to the slightly lower ionization cross section of H_2O compared to Argon. The results are shown in Figs. 8 and 9.

In summary, the inclusion of the static gas has yielded some of the trends observed by prior experiments for positive angles while other physics effects are needed for negative angles. In the future, we will implement physics modules to include the effects of stimulated desorption and a dynamic gas.

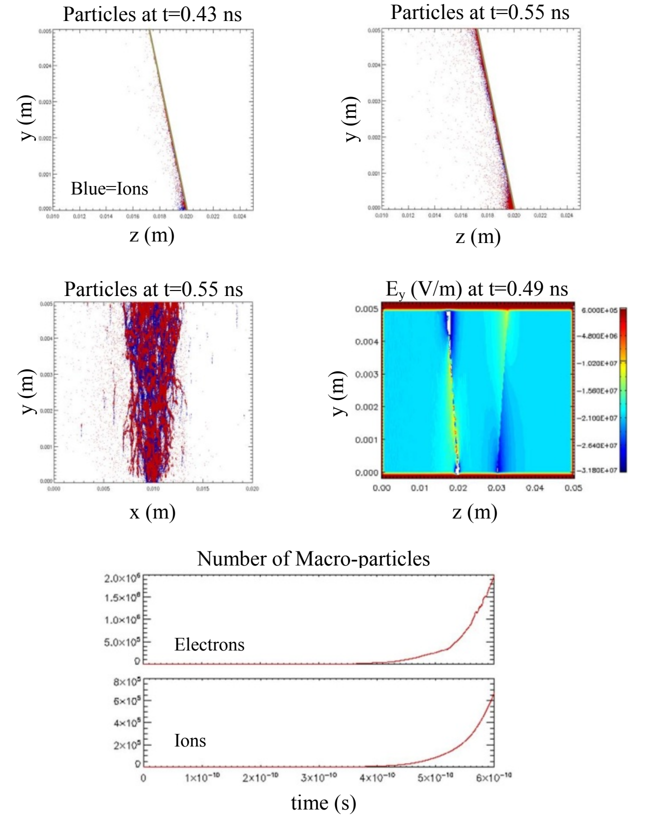

Fig. 5. The electrons (red), ions (blue), and E_y for a -30° insulator including a static gas (Argon) that includes ionizing collisions at different times.

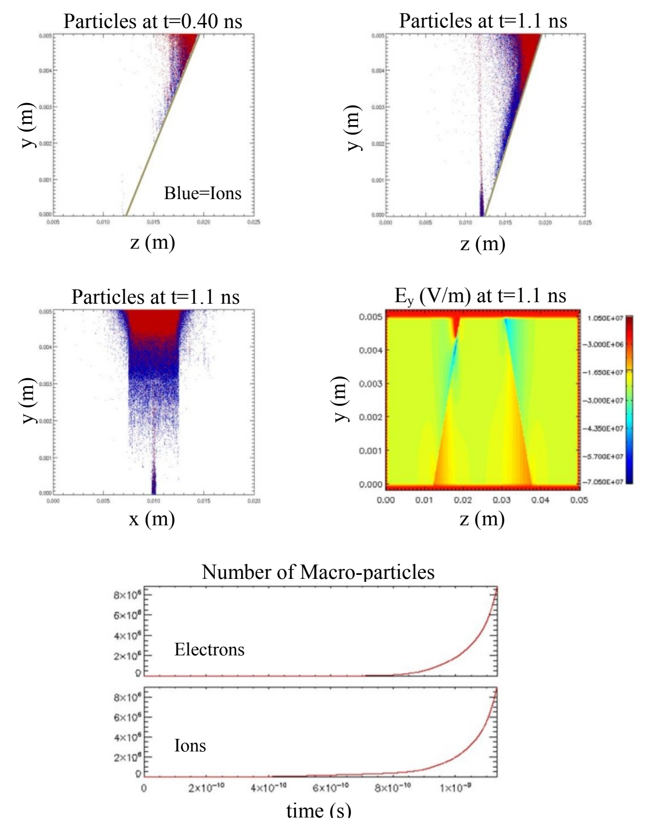

Fig. 6. The electrons (red), ions (blue), and E_y for a +55° insulator including a static gas (Argon) that includes ionizing collisions at different times.

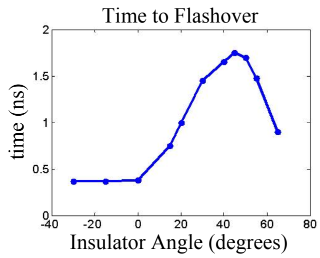

Fig. 7. The time to flashover for insulators at different angles with a static gas (Argon) that decays as Distance^{-2} and can be ionized.

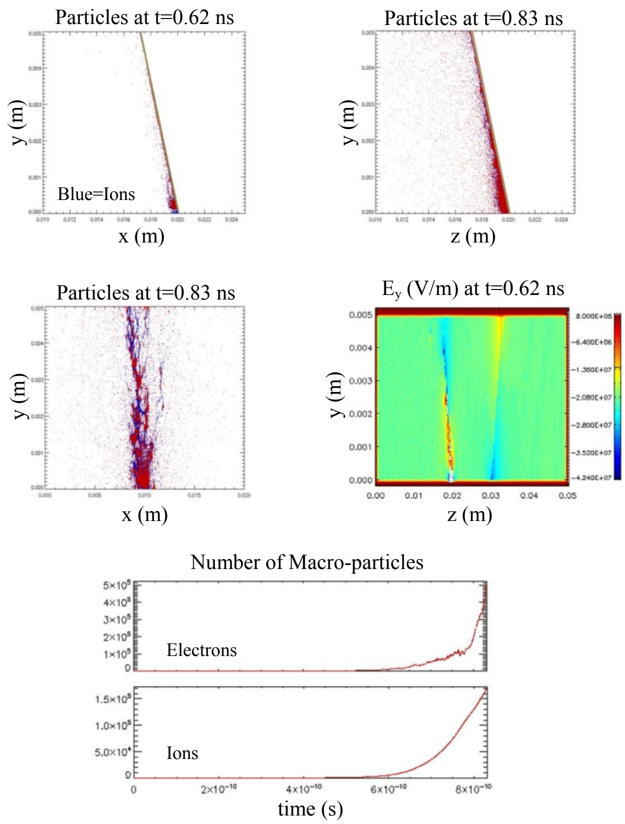

Fig. 8. The electrons (red), ions (blue), and E_y for a -30° insulator including a static gas (H_2O) that includes elastic, inelastic, and ionizing collisions at different times.

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REFERENCES

[1] VORPAL is available from Tech-X Corporation, 5621 Araphoe Ave., Suite A, Boulder, CO, 80303, http://www.txcorp.com.

[2] M.P. Perkins, T.L. Houck, J.B. Javedani, G.E. Vogtlin, and D.A. Goerz, "Progress on simulating the initiation of vacuum insulator flashover," Digest 17th Inter. IEEE Pulsed Power Conf., 2009, p. 441.

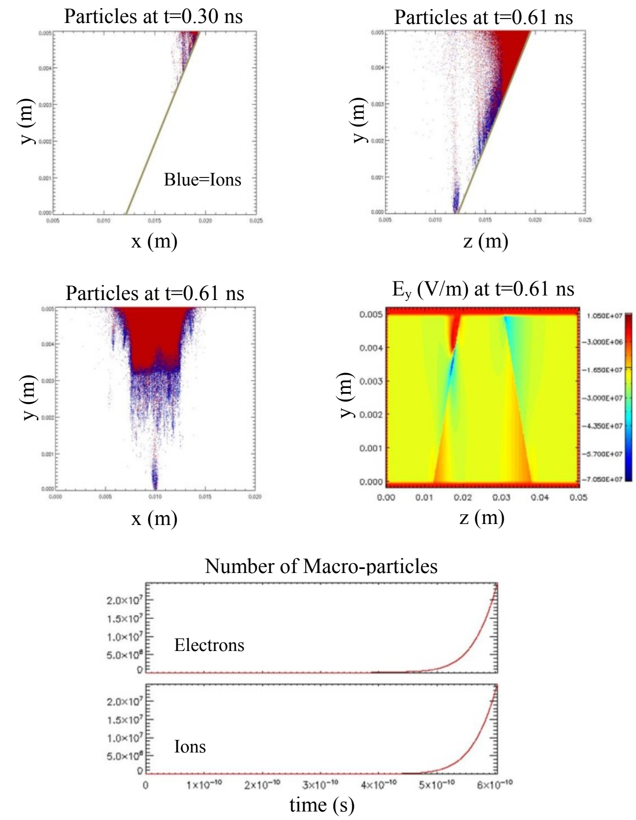

Fig. 9. The electrons (red), ions (blue), and E_y for a +55° insulator including a static gas (H_2O) that includes elastic, inelastic, and ionizing collisions at different times.

[3] T.L. Houck, D.A. Goerz, J.B. Javedani, E.J. Lauer, L.K. Tully, and G.E. Vogtlin, "Study of Vacuum Insulator Flashover for Pulse Lengths of Multi-Microseconds," Proc. Linear Accel. Conf., 2006, p. 610.

[4] J.B. Javedani, et. el., "Understanding High Voltage Vacuum Insulators for Microsecond Pulses," 16th IEEE Puls. Pow. Conf., 2007, p. 1836.

[5] J.B. Javedani, T.L. Houck, B.T. Kelly, D.A. Lahowe, M.D. Shirk, and D.A. Goerz, "UV Induced Insulator Flashover," Proc. 28th IEEE Int. Power Mod. and High Voltage Conf., 2008, p. 33.

[6] L.K. Tully, A.D. White, D.A. Goerz, J.B. Javedani, and T.L. Houck, "Electrostatic Modeling of Vacuum Insulator Triple Junctions," Proc. 16th IEEE Pulsed Power Conf., 2007, p. 1195.

[7] T.P Hughes, H. Davis, "Effect of Stimulated and Thermal Desorption in Darht-2," Proc. 2003 Particle Acclerator Conf., 2003, p. 120.

[8] G.G. Raju, "Collision Cross Sections in Gaseous Electronics. Part II. Inelastic Collisions," IEEE Elec. Ins. Mag., Vol. 23, Iss. 2, 2007, p. 17.

[9] Y. Itikawa and N. Mason, "Cross Sections for Electron Collisoins with Water Molecules," J. Phys. Chem. Ref. Data, Vol. 34, No. 1, 2005, p. 1.

[10] M. Yousfi, and M.D. Benabdessadok, "Boltzmann Equation Analysis of Electron–Molecule Collision Cross Sections in Water Vapor and Ammonia," J. of Applied Phys., Vol. 80, Iss. 12, 1996, p. 6619.

[11] D.V. Rose, D.R. Welch, C.Thoma, "Computational Modeling of High Pressure Gas Breakdown and Streamer Formation in External Electric Fields," Digest 16th Inter. IEEE Pulsed Power Conf., 2007, p. 1205.

[12] C.K. Birdsall, "Particle-in-Cell Charged-Particle Simulations, Plus Monte Carlo Collisions with Neutral Atoms, PIC-MCC," IEEE Trans. Plasma Sci., Vol. 19, Iss. 2, 1991, p. 65.

[13] I.D. Smith, "Pulse Breakdown of Insulator Surfaces in a Poor Vacuum," Proc. 1st International Symp. On Insulation Of High Voltages In Vacuum, 1964, p. 261.