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Investigations of Vacuum Insulator Flashover in Pulsed Power Systems

Matthew Hopkins
Applied Optical and Plasma Sciences
Sandia National Laboratories
Albuquerque, USA
mmhopki@sandia.gov

William Brooks
Center for Pulsed Power and Power Electronics
Texas Tech University
Lubbock, USA
william.c.brooks@ttu.edu

Raimi Clark
Center for Pulsed Power and Power Electronics
Texas Tech University
Lubbock, USA
raimi.clark@ttu.edu

Zakari Echo
Thermal/Fluid Component Sciences
Sandia National Laboratories
Albuquerque, USA
zeckert@sandia.gov

Ronald Goeke
Analytic and Materials Sciences
Sandia National Laboratories
Albuquerque, USA
rsgoeke@sandia.gov

Christopher Moore
Plasma Theory and Simulation
Sandia National Laboratories
Albuquerque, USA
chmoore@sandia.gov

Michael Mounho
Center for Pulsed Power and Power Electronics
Texas Tech University
Lubbock, USA
michael.mounho@ttu.edu

Andreas Neuber
Center for Pulsed Power and Power Electronics
Texas Tech University
Lubbock, USA
andreas.neuber@ttu.edu

Jacob Stephens
Center for Pulsed Power and Power Electronics
Texas Tech University
Lubbock, USA
jacob.c.stephens@ttu.edu

Jacob Young
Center for Pulsed Power and Power Electronics
Texas Tech University
Lubbock, USA
jacob.k.young@ttu.edu

***Abstract*—This presentation describes a new effort to better understand insulator flashover in high current, high voltage pulsed power systems. Both experimental and modeling investigations are described. Particular emphasis is put upon understand flashover that initiate in the anode triple junction (anode-vacuum-dielectric).**

***Keywords*—insulator flashover, vacuum arc, electrical discharge, plasma**

I. Introduction

Insulator flashover is a catastrophic failure mechanism in many pulsed power systems. For high current, high voltage operation, a typical pulsed power system will have a water (or oil) section adjacent to a vacuum section. While the vacuum section is more resistant to breakdown than water (or a dielectric), the interface between the fluid and vacuum section is a dielectric insulator and breakdown, or flashover, events take place along the dielectric surface. Mitigating this breakdown is often a key driver for the cost of a large-scale pulsed power systems, such as the Z Machine at Sandia National Laboratories, as well as the next generation pulsed power (NGPP) system currently being developed (see Figure 1 and TABLE I.). This presentation will present a new effort in capturing practical and theoretical aspects of vacuum insulator flashover using both experiments and modeling. In particular, the developing of an anode-initiated breakdown at the anode triple junction (anode-dielectric-vacuum) is investigated as this breakdown process has significant gaps in understanding.

A key unknown is the initiation of a flashover that initiates at the anode. In the region of the pulse where currents and voltages are rising, emission from the cathode will initiate a flashover if the dielectric insulator geometry allows an electron cascade to occur (the “-45 degree” insulator configuration). However, if the dielectric geometry avoids this (e.g., the “+45 degree” insulator configuration), then flashovers sometimes initiate at the anode triple junction. If this occurs then the current pulse is interrupted, the current shunts along the insulator instead of going downstream, and the shot is essentially a failure because the load did not see the current drive needed. In contrast, when the pulse falls after the peak, the polarity of the AK gap switches and what was the anode in the rising portion of the pulse is now the cathode, and an electron cascade can (and usually does) occur causing a flashover on the back end. This, however, is not considered catastrophic as it occurs after the primary energy is delivered to the load.

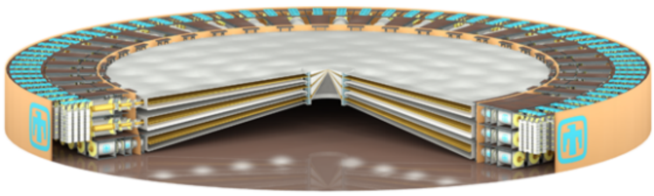

Figure 1) Design candidate for NGPP. It contains 6 AK levels (Sandia’s Z Machine currently has 4). If all technologies can successfully scale from Z to NGPP (unlikely assumption), this device would be ~90 m in diameter.

TABLE I. Comparison of NGPP parameters with current Z Machine parameters.

Parameter	**Nominal NGPP Option**	**Current Z Machine**
Machine Diameter	90 m	30 m
Marx Generators	75 @ 2400 kJ (180 MJ total)	36 @ 600 kJ (22 MJ total)
Capacitors	13,500 @ 2.95 µF	2,160 @ 2.65 µF
Power at Insulator Stack	602 TW	85 TW
Forward Energy at Insulator Stack	54 MJ (short pulse)	6 MJ (short pulse)

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II. EXPERIMENTS

Experiments allowing for enhanced diagnostics are ongoing at Texas Tech University. The flashover system consists of a hemispherical anode set into a dielectric, which in turn sits on a planar cathode (see Figure 2). At a nominal 6 mm gap and peak pulse voltage of 240 kV, we can achieve 400 kV/cm fields, although breakdown usually occurs at a lower voltage in the pulse, as desired for investigating flashover. Pulse rise times are ~40 ns. This configuration allows us to approximate the electric field environment seen on a single insulator section on the Z Machine, albeit for shorter times. Figure 3 shows current and voltage waveforms from a shot that breaks down at ~25 ns into the pulse. In many systems we require the use of an artificial field enhancement (e.g., wire protrusion), and developing approaches to avoid this artificial enhancement is a current topic of investigation. One approach is to go to even higher voltages, and this is being pursued.

By employing spectral diagnostics via optic fiber and focusing lenses, we can acquire very fast spectral information. An example is shown in Figure 4 where we see the presence of fluorine very early in the flashover initiation. In this experiment, fluorine is only introduced via the PTFE insulator giving insight into the question of where the very initial gas species required for initiation are generated.

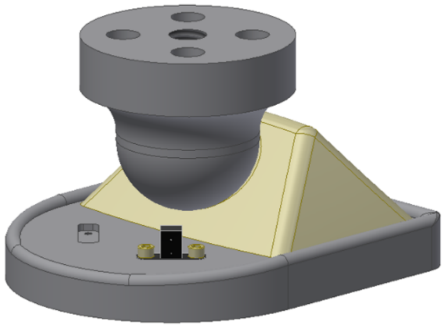

Figure 2) Depiction of experimental setup showing hemispherical anode (top), planar cathode (bottom), dielectric surface (beige angled feature in the middle), and the optic fiber stand aimed at the center line in the anode triple junction. Note the +45 degree insulator configuration.

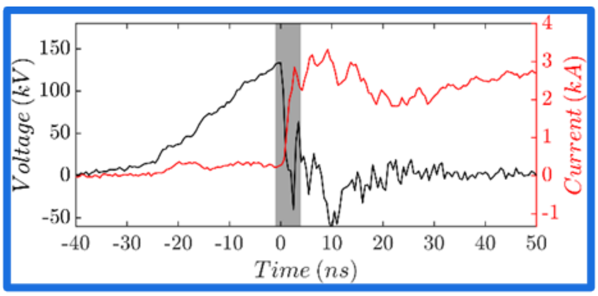

Figure 3) Voltage and current waveforms for a shot. This shot broke down at ~130 kV. The grey rectangular region indicates where light emission was collected (~5 ns collection time).

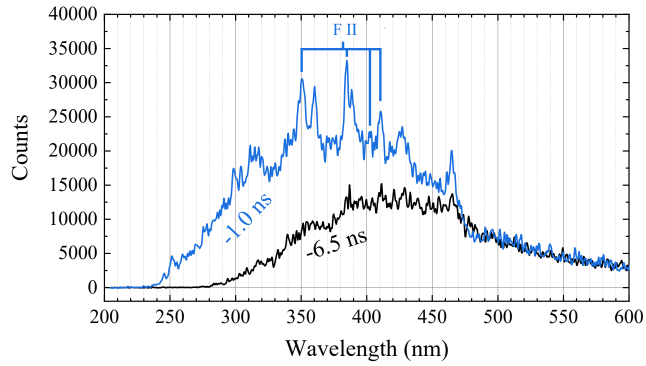

Figure 4) Spectrum for the gated region in prior figure right at initiation. Note the presence of F II emissions indicates material from the insulator has been ionized.

III. MODELING

The modeling approach uses Aleph, a massively parallel electrostatic particle-in-cell direct simulation Monte Carlo method. It includes unstructured meshes (allowing smaller cells where plasma density is expected to be high), and dynamic particle weighting (to track exponentially growing plasma constituent densities). We include molecular parent species of H_2, C, O_2, H_2O, and CO_2. A moderately complex set of plasma chemistry interactions are included, including e-neutral ionization, excitation, elastic, dissociative, and attachment collisions. Heavy-heavy interactions are also included (e.g., charge exchange). Photonic processes are modeled for radiative decay, creating photons which can go on to photoexcite and photoionize other species, or photoemit electrons from surfaces. Including children species, we track approximately 60 atomic and molecular species. A sample mesh for a 2D 2.5 mm gap is shown in Figure 5, and a nominal result in a 1 mm gap shown in Figure 6. We have simulated full 6 mm gaps (in 2D).

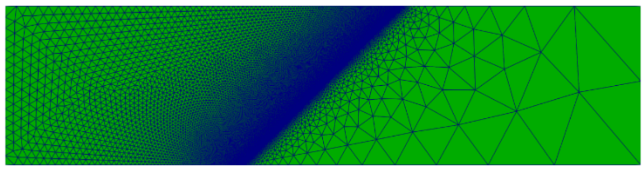

Figure 5) 2D mesh for 2.5 mm gap. Upper boundary is anodic with V(t) defined by waveform from experiment (rise only). Bottom boundary is cathodic (V = 0). Angled white line is the interface between vacuum (left) and dielectric (right). Using unstructured meshes, the mesh size at the interface is Δx = 100 nm, which grows to Δx = ~150 μm in the vacuum edge, and Δx = 1.25 mm in the dielectric edge (maximum/minimum cell size ratios of ~1,500x and ~13,000x, respectively). There is negligible activity at the edges in this vacuum system.

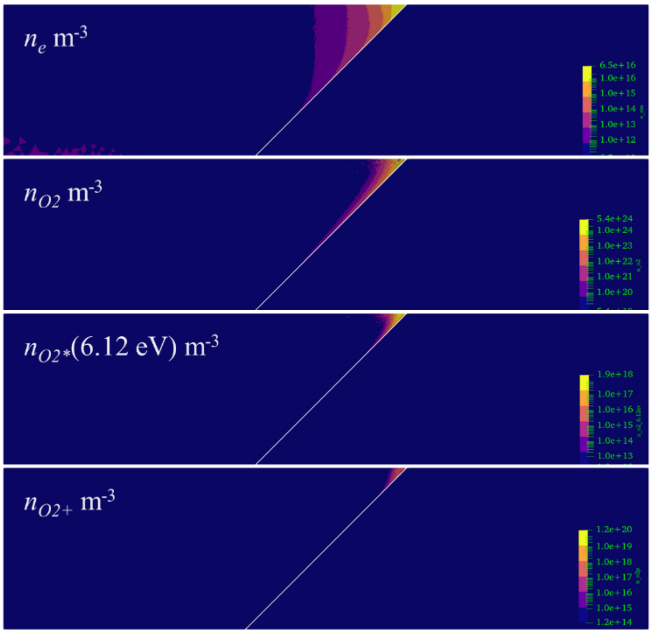

Figure 6) From a simulation with gap = 1.0 mm, and a peak voltage of 40 kV (yielding the same bulk field of 400 kV/cm), number densities are shown for e-, O_2, O_2+, and O_2(6.12 eV) from top to bottom. This is at t = 40 ns when the maximum field has been achieved. Note the 6-order log scales; the peak densities are in a very small region in the anode triple junction region (~100 µm).*

The physics of extracting electrons and neutrals from a dielectric are not well understood; this model naively assumes that the electrons are emitted via Fowler-Nordheim emission, and that the neutral emission flux is a constant multiple of electron emission. An observation from the simulations is that as electron emission occurs, leaving behind a net positive surface charge, the normal field magnitude is reduced, thus reducing the field emission. This is demonstrated in Figure 7. This negative feedback is likely critical to understanding the physics of anode triple junction initiation and evolution.

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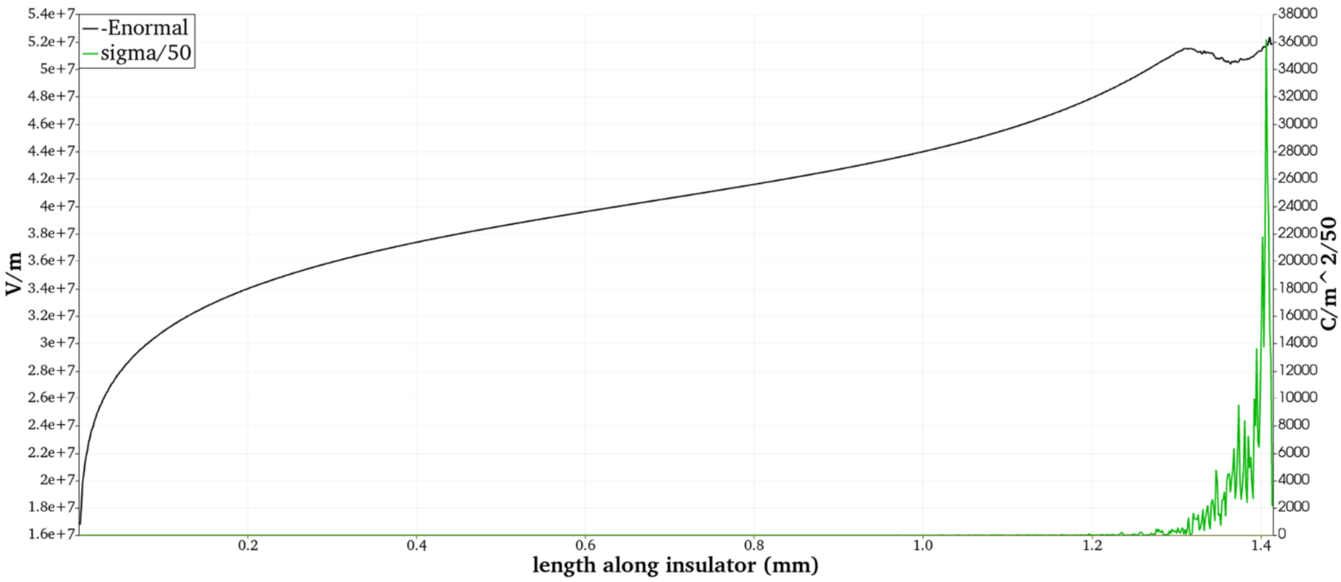

Figure 7) The negative normal electric field at the interface is shown (-E_{normal} = $\mathbf{E}\cdot(1,-1)$) in black, corresponding to the left axis. Surface charge density is shown in green and corresponds to the right axis. This shows the impact of accumulated surface charge on the dielectric near the anode triple junction.