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Temporally resolved light emission and optical emission spectroscopy of surface flashover in vacuum

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***Abstract*— Early light emission provides information about the dominant mechanisms culminating in vacuum surface flashover (anode-initiated vs. cathode-initiated) for particular geometries. From experimental evidence gathered elsewhere, for the case of an insulator oriented at 45° with respect to the anode, anode-initiated flashover is believed to dominate since the field at the anode triple point is roughly three times that of the cathode. Similar to previous work performed on cathode-initiated flashover, light emission from the voltage rise through the impedance collapse is collected into two optical fibers focused on light emanating from the insulator in regions near the anode and cathode. The optical fibers are either connected to PMTs for spectrally integrated localized light intensity information or to a spectrograph used in conjunction with an ICCD camera. Challenges associated with localizing the flashover for optical diagnostics and incorporating the optical diagnostics into the high-field environment are discussed. Initial results for cross-linked polystyrene (Rexolite 1422) support the premise that flashover is initiated from the anode for these geometries, as early light from the anode leads cathode light up to photocathode saturation. Early spectroscopy results show promise for future characterization of the spatio-temporal development of emission from desorbed gas species across the insulator surface and identification of bulk insulator involvement if it occurs.**

Keywords—surface flashover, optical diagnostics, light emission, spectroscopy, anode-initiation

I. Introduction

Surface flashover is of primary concern in high voltage vacuum systems because it often limits the maximum energy deposition into a load. Cathode-initiated surface flashover, the dominant mechanism for most symmetrical anode-cathode-insulator geometries, is relatively well understood. However, an examination of anode-initiated flashover, which is suspected to predominate for geometries where the insulator is oriented at 45° with respect to the anode (positive 45° geometry) due to the enhanced field at the anode triple junction, is less mature. It is noted that this constitutes a very typical geometry for large-scale pulsed power devices, and thus there is interest in gathering experimental evidence for a more complete theoretical basis for anode-initiated flashover. Spectroscopic techniques have previously been used to interrogate cathode-initiated flashovers across planar and cylindrical geometries (0° geometries), leading to the identification of desorbed gasses and cathodoluminescence [1] and quantification of plasma temperatures [2].

II. Experimental Setup

A. Flashover Fixture

Insulator stacks in typical large-scale pulsed power devices are often axially symmetric, ring-like structures; subsequently a flashover is liable to occur anywhere along the circumference of the insulator. In the interest of improved diagnostic accessibility, a flashover fixture was designed with a hemispherical anode in an effort to localize the flashover, see Fig. 1. The anode-cathode gap distance is 6 mm, resulting in a path length across the desired flashover locations of ~8.5 mm. The cathode is secured to a stand which serves to provide optical access through viewports in the vacuum chamber. The fixture is located in a vacuum chamber with typical experiment pressures on the order of 10^{-6} torr. The source is an eight-stage, 240 kV pressurized Marx generator, and the peak voltage reached in an experiment is determined by the flashover hold-off of the system. For a peak voltage of 140 kV, the peak electric field on the vacuum side of the anode triple junction is simulated to be just over 500 kV/cm. The rise time varies within a few nanoseconds due to the shot-to-shot variation in peak voltage, but a typical value is between 10-20 ns. The insulator is cross-linked polystyrene (Rexolite 1422), which has previously been demonstrated to exhibit improved flashover characteristics over polymers with comparable vacuum properties [3]. A coaxially-integrated capacitive voltage divider and current viewing resistor provide voltage and current waveforms.

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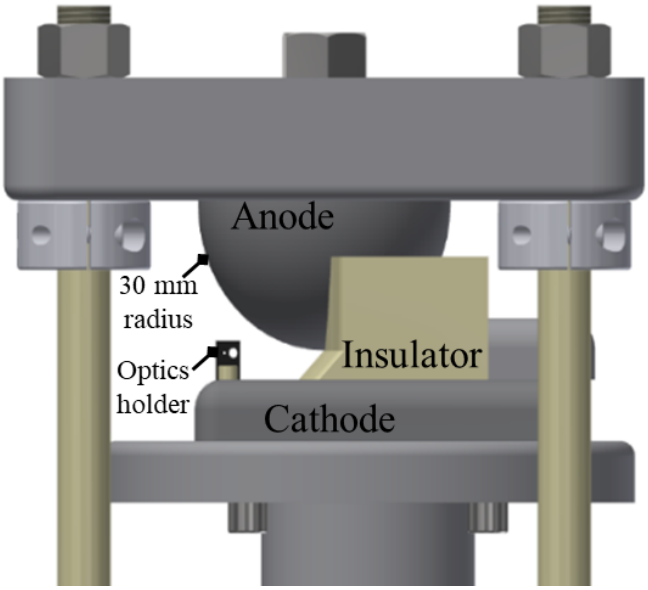

Fig. 1. Flashover fixture with positive 45° insulator geometry.

Even with the reduced size geometry, localizing the flashover has proven to be difficult. For the initial insulator design depicted in Fig. 1, with a short angled surface extending into a vertical face, the flashover often preferred spreading laterally across the vertical face or at the junction of the faces. A subsequent design where the 45° face extends through the height of the insulator (c.f. Fig. 2.b.) marked a substantial improvement to the voltage hold off; however, the flashover migrated to the back and sides of the insulator. While there is ongoing improvement to the insulator design, in the interest of collecting initial optical data, a 0.5 mm diameter aluminum wire was used as a field enhancement to localize the flashover to the intended anode-cathode gap.

B. Spatially-resolved Light Collection

The spatially resolved optical diagnostics selectively collect light from the insulator in regions near the anode and the cathode via optical fibers and rod lens pairs. The PEEK lens holder and resultant light collection regions are depicted in Fig. 2. The anode and cathode spot sizes are roughly 2.5 mm tall with 1 mm separation. The lens holder is located in a pocket on the cathode ~20 mm away from the insulator face. The fibers feed out of the vacuum chamber and into a screen room, where various diagnostic devices are employed. Thus far, light emission has been examined with Thor Labs PMT-SS modules with 1.4 ns rise time and 185-900 nm spectral response to examine temporally resolved, spectrally integrated light intensity. No neutral density filtering is used since early light is of primary interest. While this results in saturation of the PMTs prior even to the impedance collapse, the desired differences in the early intensity from the insulator regions are well resolved, and the pulse is short enough that the length of saturation does not damage the diagnostics. Spectroscopy is performed with an Andor Kymera 193i spectrograph and a PI-MAX4 intensified CCD (ICCD) camera. The fibers are coupled into a collimator and directed

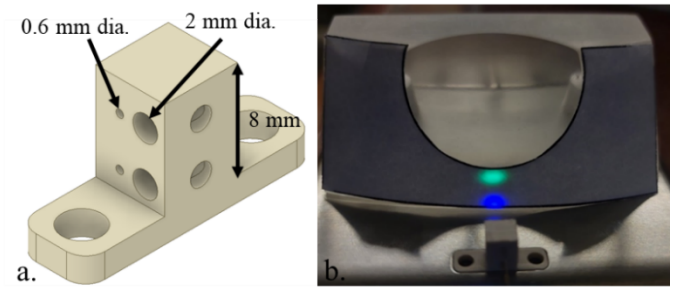

Fig. 2. a.) Optics holder consisting of two channels with two fused silica cylindrical lenses each. The fibers abut the 0.6 mm dia. lenses. b.) The anode (green, top) and cathode (blue, bottom) light collection regions projected onto the insulator. The insulator surface is covered with paper for photographing purposes only.

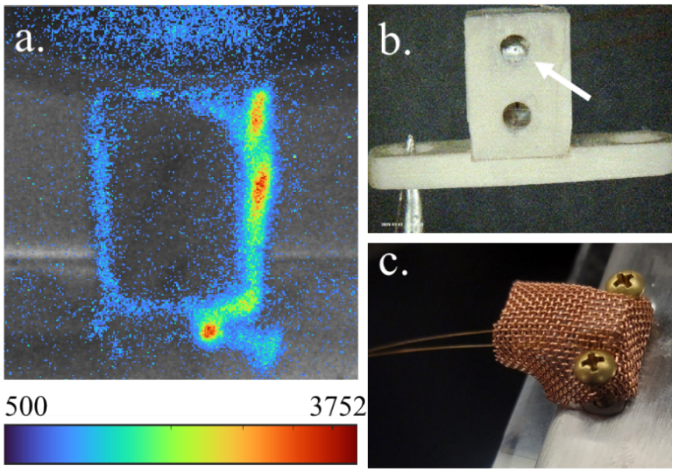

Fig. 3. a.) Psuedo-color ICCD image (log scale) of flashover across the lens holder. b.) Metal deposition from anode on lens as a consequence of the flashover. c.) Mesh shielding installed around lens holder to raise ground potential above lens holder surfaces.

through the input slit of the spectrograph, set to 50 µm width.

Initial shots with the lens holder integrated into the experiment caused the discharge to bridge the vacuum gap between the anode and the lens holder and flash along the surface of the lens holder rather than the insulator. A pseudo-color ICCD image of one such occurrence is shown, see Fig. 3.a. It is believed that the vertical surface of the lens holder allowed for the development of a secondary emission avalanche, which released sufficient desorbed gas from the plastic to cause breakdown across the gap. When this occurred, significant pitting was observed at the anode, and debris from the anode was deposited on and around the lenses, see Fig. 3.b. – markedly reducing their ability to gather light. Subsequently, it was necessary to incorporate some protection to both deter the spark from flashing across the lens holder rather than the intended insulator surface and limit the contamination of the lenses. Initially, a field-shaping ring was considered, but the idea was rejected due to the extremely limited space between the optics holder and the anode. Instead, a fine copper mesh was shaped around the optics holder and screwed into the locating pocket for electrical connection to the cathode, see Fig. 3.c. This

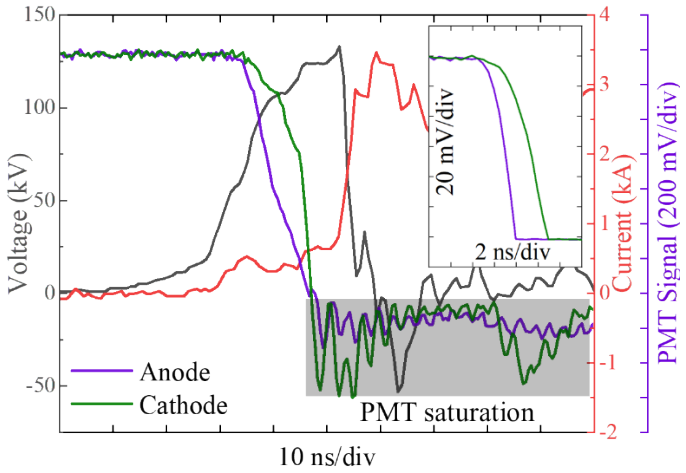

Fig. 4. Voltage (left axis), current (right axis), and light intensity waveforms (third axis) for a shot on a pristine insulator. Early anode light precedes cathode light. The inset graph shows that early light resolved 10x more finely through a parallel scope channel set to a higher sensitivity.

serves to raise the ground potential above the vertical surface of the optics holder to prevent the development of the secondary electron avalanche. Holes are carefully located in the mesh to leave the optical path unimpeded. Admittedly, due to the small gap size and the field enhancements from the fine features on the mesh, there was appreciable doubt that this would be effective; however, most of the fabricated mesh protectors have staved off breakdown to the lens holder for upwards of 30 shots.

III. Results

A. Early light emission

Preliminary results have indicated that early light originates at the anode for a flashover across a pristine insulator. Voltage, current, and light intensity waveforms are given for the first shot across an insulator, see Fig. 4. The optical and electrical diagnostic signals are timed to within one nanosecond. The first light is detected when the voltage has risen to ~60 kV. Initially, the early light from the anode rises more quickly than light from the cathode, and the anode light precedes the cathode light up until PMT saturation, which occurs just a few nanoseconds prior to the impedance collapse. Note that the ripples in the area indicated as saturation are an artifact of the diagnostic setup; it has been tested and confirmed that the devices are being driven into saturation. This supports the premise that flashover is initiated at the anode for the 45° geometry. For repeated shots on the same insulator, i.e. within a single pump-down of the vacuum chamber, the time lead of the anode light is repeated for a number of shots; however, beyond ten or so shots the difference in the waveforms appears to become noticeably less pronounced.

B. Spectroscopy

Initial data have been taken with a 1200 g/mm diffraction grating. Subsequently, emission lines are fairly well resolved, but only limited portions of the emission spectra can be observed in a single shot. Future improvements to the

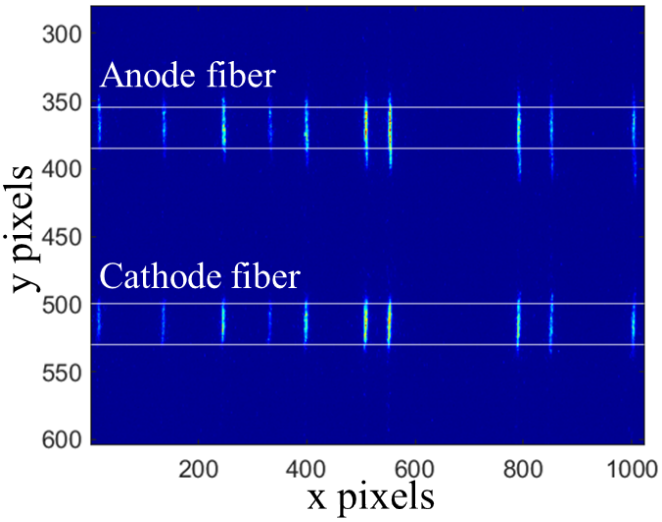

Fig. 5. Demonstration of spatial resolution from fibers on ICCD pixel array (continuous neon lamp source). Light from each fiber is separated by >100 pixels and each signal can be binned over ~30 pixels (horizontal white lines indicate height of bins).

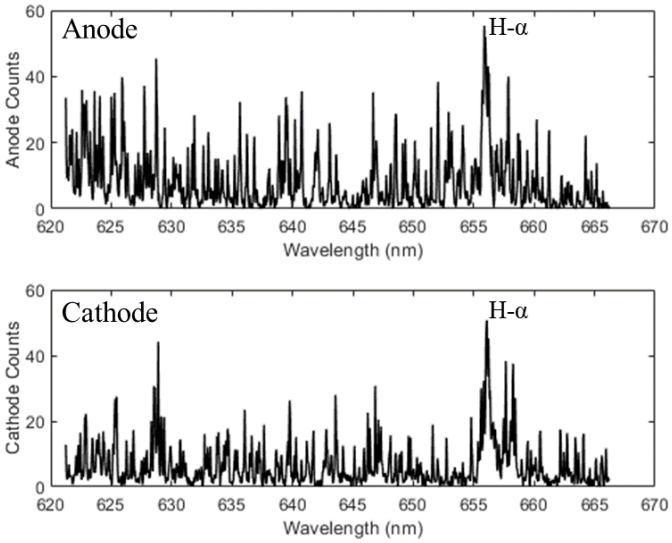

Fig. 6. Initial spectroscopy result taken with a 75 ns gate and 50 µm slit. The H-α line is identifiable for both anode and cathode light amongst many other spectral lines which may be attributable to metal species from the electrodes.

spectroscopy setup will allow for the capture of larger portions of the spectra within a single shot, but this early work has demonstrated successful use of the fibers for spatially resolved spectroscopy. The separation of the light from the anode and cathode fibers on the ICCD is demonstrated by imaging of the spectral lines from a continuous neon arc lamp source, see Fig. 5. The light from the two fibers are separated by over 100 pixels, with light from each fiber covering a height of roughly 30 pixels which are separated into a bin.

An initial spectroscopy result, with the H-α line identified, is given in Fig. 6. The wealth of other lines in the region may be attributable to luminescence from metal species in the electrodes, which will continue to be investigated in future work. These spectra were captured with a 75 ns gate time,

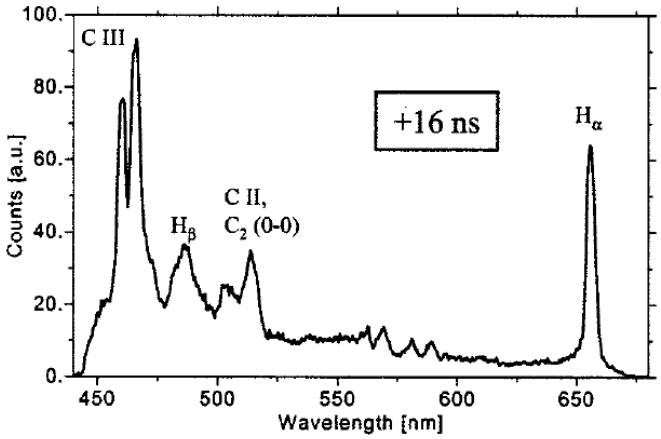

Fig. 7. Time resolved (16 ns post-impedance collapse) spectra of slow-rise, cathode-initiated flashover from Neuber et al. [1] (©2000 IEEE).

covering the entire voltage rise and roughly 50 ns after the impedance collapse. For this length of gate, the anode and cathode spectra appear fairly similar because both the onset and the fully-developed state of the spark are being observed – the temporal development of the species across the insulator surface is not captured. However, it is expected that with further experimentation, and specifically moving to a diffraction grating with fewer grooves per millimeter and narrowing the gate time on the ICCD, the spatiotemporal development of the emission species can be quantified. Specifically, there is interest in examining time scales for the appearance of carbon emission lines, which may indicate an onset of bulk insulator involvement in the flashover. With sufficient data, comparison will be possible with previous work on cathode-initiated flashover, for instance that of Neuber et al. One such spectra from slow rise, cathode-initiated flashover over alumina is provided for reference, see Fig. 7 from [1]. This work found little evidence of bulk insulator involvement in the early phase of flashover, so if it is identified for the conditions presented here, it would indicate a marked difference in the physical mechanisms of the flashover process.

IV. Conclusions

A compact, laboratory-scale vacuum flashover fixture to analyze the positive 45° insulator geometry has been developed with notably improved diagnostic accessibility over the traditional ring-like structure. Simultaneous, spatially resolved optical diagnostics were successfully developed to interrogate light emission from insulator regions adjacent to the anode and cathode within a single shot. While there is ongoing design work to localize the flashover location without the need for a field enhancement, early light intensity results support the premise that flashover is initiated at the anode for these geometries. Anode light has consistently led cathode light for the first shots on pristine insulators, and the trend appears to continue for a number of subsequent shots as well. Early spectroscopy results show promise for capturing the spatio-temporal development of emission species from the voltage rise through the impedance collapse in the future.

V. Acknowledgments

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