Optical Emission Spectroscopy of Atmospheric Pressure Plasma Jet Interacting with Thin Liquid Surface Film

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The interaction of atmospheric pressure plasma jets (APPJs) with liquid films on solid substrates is important in plasma medicine. The plasma interacts with the liquid film in many ways, one being evaporating or desorbing the film. This evaporation can have at least three components – simple thermal desorption, UV photolysis (and ablation), or ion bombardment (or sputtering). We are investigating the manner in which APPJs remove mass from liquid films. This is important not only to the in-liquid processes but also to the gas phase plasma properties, as the species convecting from the liquid into the plasma affect the properties of the plasma.

The test system is an APPJ sustained in helium emerging into open air. The APPJ consists of a quartz tube with ring grounded and rf-powered electrodes. The jet impinges perpendicularly onto a dielectric substrate covered with a layer of water. Time-averaged optical emission was collected from the region near the substrate surface – with OH emission ($A^2\Sigma^+ \rightarrow X^2\Pi$) at 309 nm being monitored to track water vapor. Preliminary results of the emission intensity vs. time are shown in Fig. 1, and demonstrate the plasma induced evaporation cycle. Emission commences at a low value increasing to a maximum, and then dropping relatively quickly, reaching the background level. Time-resolved (10ns resolution) emission of OH leads us to conclude that the most likely pathway producing the observed emission is dissociative excitation of water by helium metastables – $He(^3S) + H_2O \rightarrow H + OH(A^2\Sigma^+) + He$. These results may be explained by thermally induced evaporation of the water film. Although the plasma gas is at relatively low temperature, gentle heating of the water film can still occur, over-powering the evaporative cooling of the film. The OH emission intensity increases rapidly with time as the film gets warmer and the vapor pressure of water at the surface increases, which produces more evaporation. Finally the intensity drops abruptly to the background level as the film is fully removed. The background emission is due to moisture diffusing into the helium jet from the humid air surrounding the jet. With this baseline case, we will perform experiments to quantify the contributions to mass transfer from the liquid to the plasma due to UV photolysis and ion sputtering. The substrate temperature will be controlled to vary the rate of thermal evaporation, while monitoring the emission of OH. For cold water, there will be little if any thermal evaporation, and mass removal will be dominated by UV and ion effects.

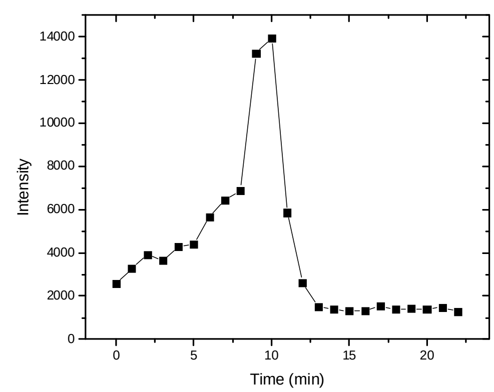

Fig. 1 – OH (309 nm) emission intensity vs. time for an APPJ interacting with a thin water surface film.

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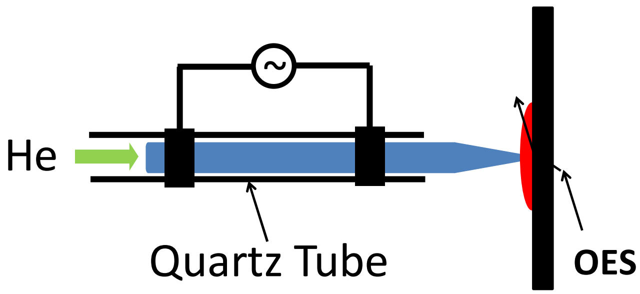
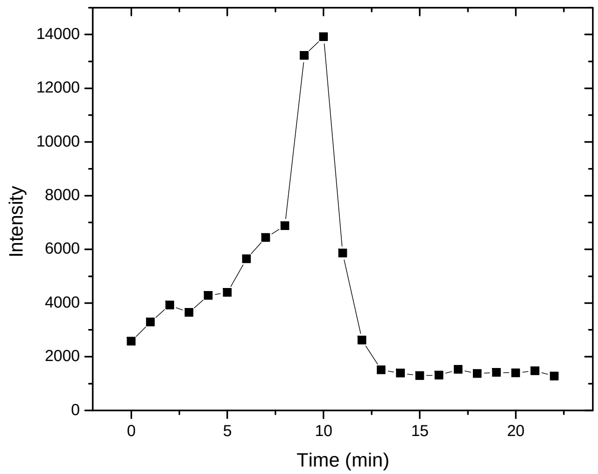
OES OF ATMOSPHERIC PRESSURE PLASMA JET (APPJ) INTERACTING WITH LIQUID SURFACE FILMS

- **The interaction of APPJ with liquid surface films involves several physical processes, including plasma accelerated evaporation by heating, UV photolysis or ion bombardment.**
- **APPJs impinging on a substrate coated with thin film of water or condensed vapors are being investigated.**
- **Desorbed/decomposed species are moni-tored by optical emission spectroscopy - OH emission at 309 nm tracks water vapor.**
- **Preliminary results (Fig. 2) suggest that heating dominates over photolysis.**
- **By changing the substrate temperature, we will isolate effect of thermal desorption in comparison to UV and ion stimulated effects.**



- **Fig. 1. APPJ interacting with liquid thin surface film.**



- **Fig. 2. OH (309 nm) emission intensity vs. time**

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Predicting High Voltage Breakdown for Plasma Switch Operation

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High power, plasma based electrical switches operating at pressures of a few Torr and higher are being investigated to improve the performance of the electric grid [1]. To deploy these switches, their lifetime and reliability must be improved, which requires improvements in our understanding of the underlying plasma physics. In this work, ionization processes and breakdown in plasma switches are being investigated for applied voltages of hundreds of kV. These conditions correspond to the left branch of the Paschen curve with pd ≈0.5 Torr-cm, where p is the gas pressure and d is the electrode separation. Breakdown has been numerically modeled using the particle-in-cell code EDIPIC which accounts for non-local transport of all species. The model includes anisotropic scattering for all species, fast neutral atom backscattering at the electrodes, as fast-neutral impact ionization, and electron back-scattering at the anode [2]. Numerical simulation of similar breakdown processes had not previously accounted for backscattering of ions and fast neutrals at the cathode. An example of a Paschen breakdown curve for helium, based on EDIPIC simulations is shown in Fig. 1, and agrees well with the available experimental data. Both computations and experiment show double-valued breakdown voltages that are not observed in the absence of accounting for non-local transport.

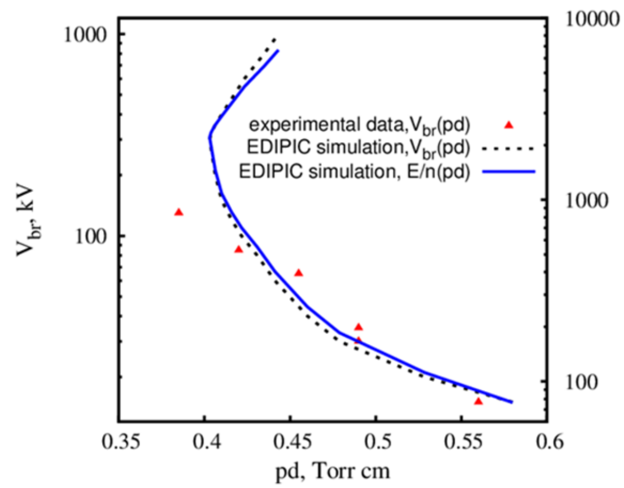


Figure 1 – The low-pressure branch of the Paschen curve for helium as predicted by EDI PIC simulations.

Back-scattered electrons are important to the ionization balance in the discharge. At these high voltages, essentially all primary electrons are in the runaway regime and their self-multiplication by collisions is small. However, backscattering of electrons at the anode produces an electron population that is of lower energy. In slowing, reversing direction and returning to the anode, the secondary electrons cross through energies where the ionization cross section may be orders of magnitude larger than for the primary electrons, and so produce disproportionally large rates of ionization.

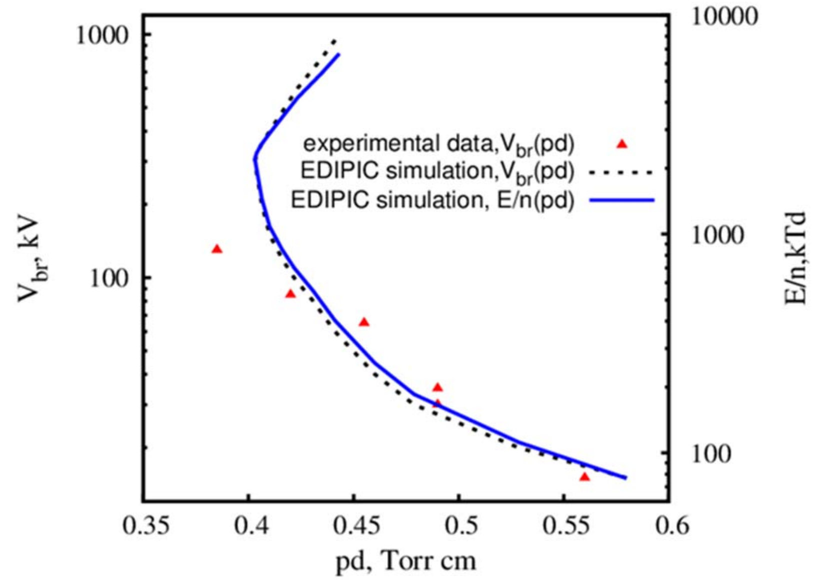
References

[1] T. J. Sommerer, “Back to the Future: How a plasma mode might change the electric power grid”, Frontiers of Plasma Science Workshops, U.S. DOE Office of Fusion Energy Sciences (2016).

[2] L. Xu, A. V. Khrabrov, I. D. Kaganovich, and T. J. Sommerer “Investigation of the Paschen Curve for Helium in 100–1000 kV Range” submitted to Phys. Plasmas (2017).

PREDICTING HIGH VOLTAGE BREAKDOWN FOR PLASMA SWITCHES

- **Magnetized DC discharges at pressures of few Torr and higher are being developed for high voltage switches in the electrical grid.**
- **Particle-in-Cell simulations using EDIPIC are being used to investigate breakdown on the low pressure side of Paschen's curve, including heavy particle ionization collisions.**
- **For potentials of > 100s kV, agreement with experiment requires anisotropic scattering, and ionization by ions, fast neutral atoms produced in charge exchange and by neutralized ions from the cathode.**



- **Low-pressure branch of Paschen's curve for helium as predicted by PIC simulations and compared with experiment.**

- **Backscattering of fast electrons at the anode surface are also important, as the secondary electrons have lower energies, which correspond to higher electron impact ionization cross sections.**

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