Electric Field Vector Measurements in Nsec Pulse Ionization Wave Discharges

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This work presents the results of time-resolved electric field measurements (i) in a ns pulse discharge in hydrogen between two plane electrodes covered by dielectric plates, and (ii) in a ns pulse, surface ionization wave discharge in hydrogen. Both results are obtained using ps four-wave mixing.

The results in a plane-to-plane discharge are compared to kinetic modeling predictions, showing good agreement, including non-zero electric field offset before the main high voltage pulse, breakdown moment, and reduction of electric field in the plasma after breakdown. Comparison with the model shows that the electric field in the nanosecond pulse discharge is controlled primarily by electron impact excitation and charge accumulation on the dielectric surfaces.

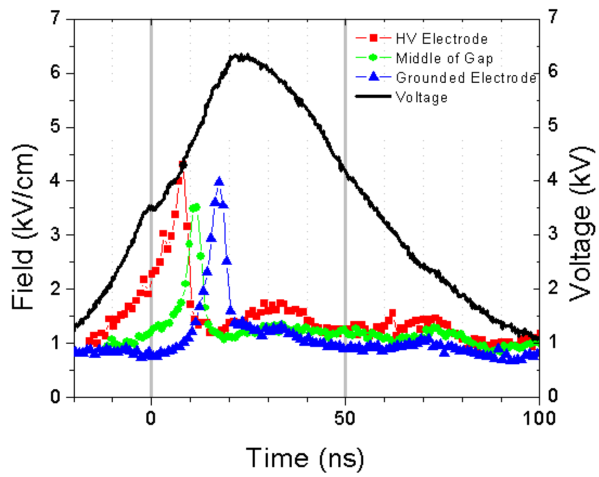

Figure 1 – Vertical electric field component measured ~ 100 µm above the surface near the high voltage electrode, halfway between the electrodes, and near the grounded electrode, plotted together with a high voltage pulse waveform and illustrating surface ionization wave propagation at an average speed of 1 mm/ns.

Two electric field vector components in the near surface discharge are measured separately, using pump and Stokes beams linearly polarized in the horizontal and vertical planes, and a polarizer placed in front of the infrared detector. The time-resolved E-field vector is measured at three locations across the discharge gap and at three different heights above the alumina dielectric surface, ~ 100 µm, 600 µm, and 1100 µm (total of nine locations). The results show that after breakdown, the discharge develops as an ionization wave propagating along the dielectric surface at a speed of 1 mm/ns. The surface ionization wave forms near the high voltage electrode, close to the dielectric surface (~100 µm). The wave front is characterized by significant overshoot of both vertical and horizontal electric field vector components. Behind the wave front, the vertical field component is rapidly reduced. As the wave propagates along the dielectric surface, it also extends further away from the dielectric surface, up to ~ 1 mm near the grounded electrode. The horizontal field component behind the wave front remains quite significant, to sustain the electron current toward the high voltage electrode. After the wave reaches the grounded electrode, the horizontal field component experiences a secondary rise in the quasi-DC discharge, where it sustains the current along the near-surface plasma sheet. The results indicate the presence of a cathode layer near the grounded electrode with significant cathode voltage fall, ≈ 3 kV, due to high current number density in the discharge. The results provide the most extensive data set available on electric field distribution in a surface ionization wave discharge, which can be used for validation of kinetic models and assessing their predictive capability.

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Highlight

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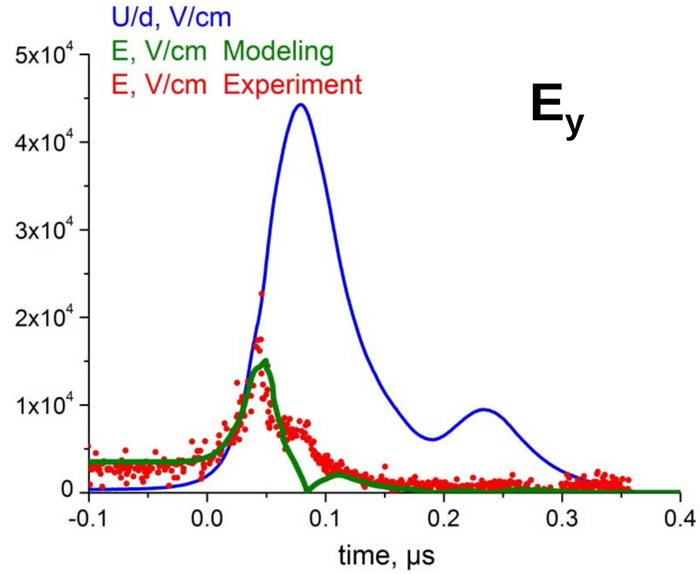
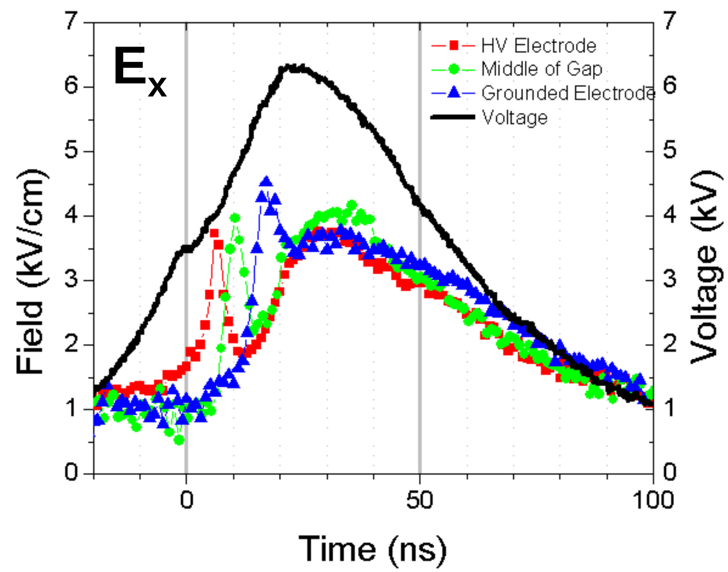
ELECTRIC FIELD VECTOR MEASUREMENTS IN PULSED PLASMAS WITH SUB-NS RESOLUTION

- **Using a newly developed ps CARS-like 4-wave mixing laser diagnostic with sub-ns resolution, time- and spatially resolved electric field vectors, $\vec{E}(t)$, are measured in plane-to-plane and surface ionization wave, nsec pulse plasmas**
- **Knowledge of $\vec{E}(t)$ is critical for quantitative insight into plasma dynamics, energy coupling and partition during ns and sub-ns pulse breakdown**



- **Transverse electric field in a plane-to-plane ns pulse discharge**



- **Axial electric field in surface ionization wave, ns pulse discharge**

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HIGHLIGHT

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Electrode Processes in Atmospheric Pressure Arc Discharge

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Anodic arc discharges with consumed anodes are used to produce various nanoparticles, including carbon nanotubes [1]. Our experiments with the carbon arc at atmospheric pressure helium demonstrate the dependence of the anode ablation rate on the anode diameter, which cannot be explained by changes of the current density at the anode. In particular, the anode ablation rate for narrow graphite anodes is significantly enhanced resulting in high deposition rates of carbonaceous products on the copper cathode [2]. The proposed model explains these results with interconnected steady-state models of the cathode and the anode processes [3]. Considering the cathode processes, the model predicts circulation of the particles in the near-cathode region, evaporation of the cathode material, ionization of evaporated atoms and molecules in the near-cathode plasma, return of the resulting ions to the cathode, surface recombination of ions and electrons followed again by cathode evaporation. In the case of a low anode ablation rate, ion acceleration in the cathode sheath provides the major cathode heating mechanism. Thus, the circulation converts the energy of the emitted electrons, accelerated inside the cathode sheath to the plasma, into the ion heat flux to the cathode.

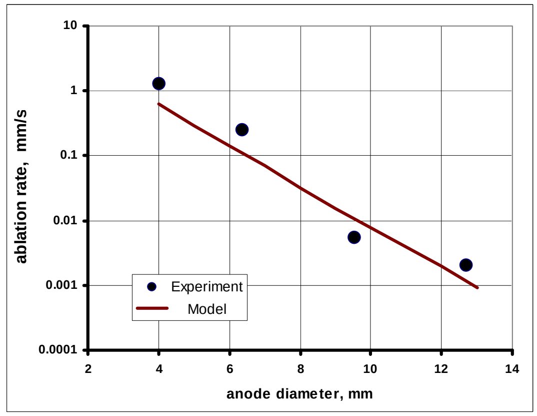


Fig. 1 – Anode ablation rate at different anode diameters. Points: experimental data [2].

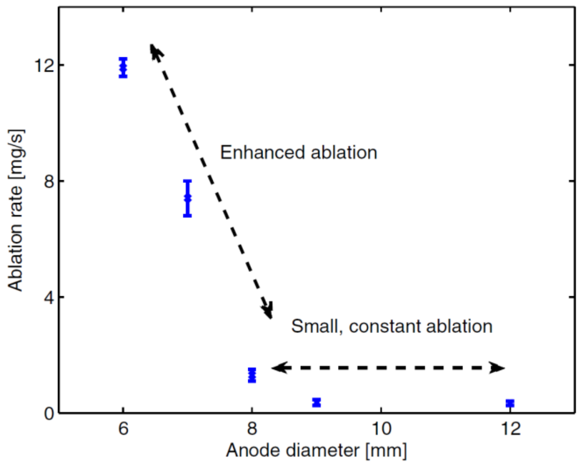
In the case of intensive anode ablation, an additional cathode heating is due to latent fusion heat of the atomic species evaporated from the anode and depositing at the cathode. Using the experimental arc voltage as the only input parameter, the model allows us to calculate, the anode ablation rate. A comparison of the results of calculations with the available experimental data shows reasonable agreement. For the heat balance at the anode, the anode is heated by the conduction heat flux from plasma. The main mechanisms that cool the anode are radiation, evaporation and thermal conduction inside the anode body. To evaluate the heat flux from the plasma to the anode, the concept of the voltage equivalent of the heat flux was used. The voltage equivalent was obtained by using results of our cathode modeling and the experimental data on the arc voltage. The model describes the large difference in the ablation rate for narrow and wide anodes observed in experiments. A comparison of calculated and measured anode ablation rates shows good agreement [3]. Several issues of the energy balance at the electrodes are to be addressed, including the anode sheath voltage drop, current conduction in the inter-electrode gap and non-steady state processes.

References

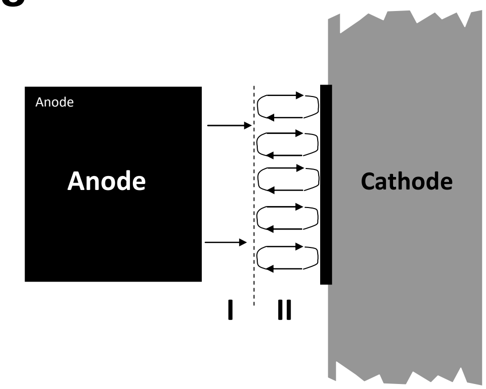
[1] C. Journet, W. Maser, P. Bernier, A. Loiseau, et al. Nature **388** (6644) 756 (1997).
[2] J. Ng, and Y. Raitses, J. App. Phys. **117**, 063303 (2015).
[3] V. Nemchinskiy and Y. Raitses, submited to J. Phys. D: Appl. Phys. (2015).

ELECTRODE PROCESSES IN ATM PRESSURE ARC DISCHARGES WITH A CONSUMED ANODE

- **Arc discharges are used for production of nano-materials (such as CNTs).**
- **Recent experiments demonstrate a constant small ablation rate for large graphite anodes resulting in a low deposition rates on the cathode.**
- **With small deposition rate, the cathode heating is seemingly insufficient to sustain the arc current by thermionic emission.**
- **An arc model predicts the ion heating of the cathode by circulation of the particles in the near-cathode region – evaporation of the cathode material, ionization of evaporated atoms and molecules in the cathode plasma, return of the resulting ions to the cathode and heating of the cathode.**



- **Anode ablation rate**



- **Model predicts a recycling of evaporated deposit particles in the cathode region**

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