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Time-Resolved Emission from the VUV to near IR of Atmospheric Pressure He Discharges into Open Air

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We have investigated He plasmas in a small quartz tube surrounded by a grounded and an rf-powered (typically 200 kHz) electrode. The plasma jet emerges into open air and impinges on either a MgF_2 window coupled to a vacuum ultraviolet (VUV) spectrometer (Fig. 1), or the flat face of a hemispherical UV grade quartz prism. UV-visible light passing through the prism is observed with a monochromator equipped with either an intensified CCD (ICCD) or CCD detector. Optical emission spectra are recorded either time-resolved or time-averaged for various geometries.

Varying the angle of refraction inside the quartz prism (θ_r) allowed light to be collected along the direction defined by the angle of incidence (θ_i). At $\theta_r = \theta_i = 0$, the full plasma extending from the discharge inside the quartz tube is probed, while at $\theta_r = 42^o$, light is collected along an angle $\theta_i = \arcsin(n \sin \theta_r) = 76^o$ from the surface, probing close to (~1 mm) the surface of the prism. Spectra contained the expected He and O emission in the red as well as UV/VUV emission from N_2, N_2^+, H, O, N, OH, and NO.

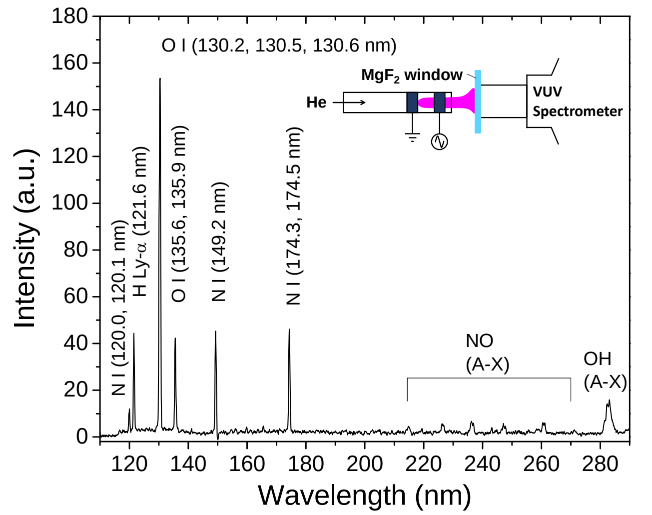


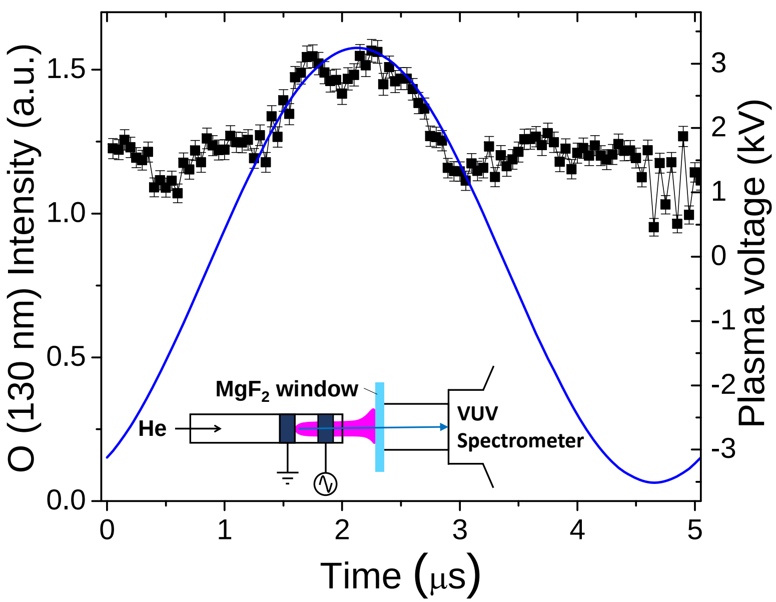
Fig. 1. Atmospheric pressure He plasma VUV spectrum.

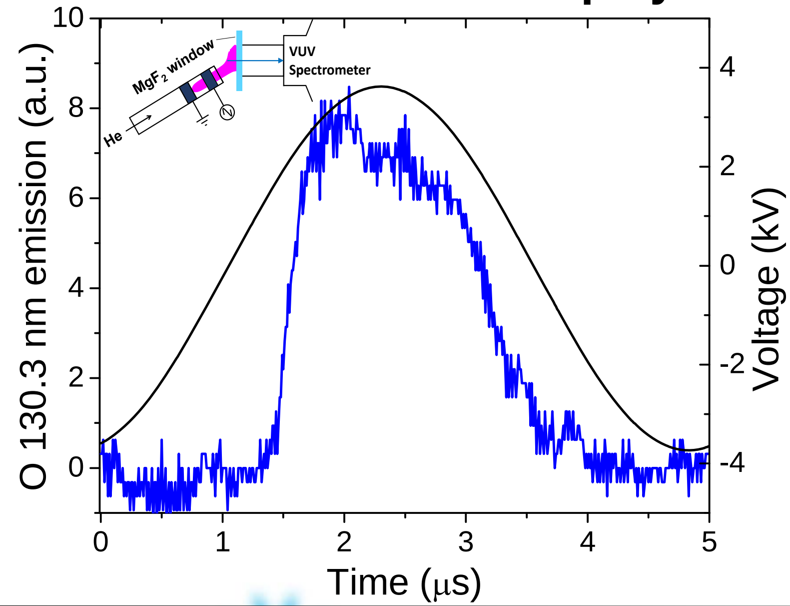
At $\theta_r = 0$, He 706 nm emission from mainly inside the discharge tube exhibits an intense feature at peak negative voltage and a less intense feature at peak positive voltage. For $\theta_r = 10\text{-}42^o$, He emission outside the tube is only detected during the positive voltage period and several hundred ns after the maximum voltage, about the time it takes the ionization wave ("plasma bullet") to travel 1.2 cm from the end of the discharge tube to the quartz surface.

With the VUV spectrometer and MgF_2 surface, emissions are from O, N, and H (Fig. 1) are detected. Even when traveling through 1 cm of air, the O_2 diffusing into the He stream does not reduce the emission intensities to undetectable levels. Time resolved O, N, OH, and N_2^+ emission along the discharge tube is only slightly modulated. Emission from $N_2(C \rightarrow B)$ is strongly modulated. Off axis emission is detected only during part of the positive voltage period and peaks ***before*** the ionization front reaches the MgF_2 surface. It was concluded that in the discharge, He and N_2 are excited mainly by electron impact, while O, N, OH, NO and N_2^+ are excited mainly by collisions of O_2, N_2, H_2O and possibly NO_2 with He metastables. Near the surface, photo-dissociative excitation by He 50.6-58.4 nm emission from the discharge tube could also be important.

TIME-RESOLVED VUV TO NEAR IR EMISSION IN 1 ATM HE DISCHARGES INTO OPEN AIR

- O 130 nm emission inside discharge tube (left) is only moderately modulated, similar to N, OH, and N_2^+ emission. Emission from He 706 nm and N_2 are highly modulated with peaks at (-) V and (+) V, and no emission in between.
- O 130 nm (right) and all other emission near the surface are fully modulated and peak near the (+) voltage.
- In the discharge, He, N_2 are excited by e-impact, whereas O, N, OH, NO, N_2^+ are excited by collisions of O_2, N_2, H_2O, NO_2 with He metastables. Near the surface, photo-dissociative excitation by He 50.6-58.4 nm emission could play a role.





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Hybrid Fluid/Kinetic Modeling of Plasma Flows Over Aerosol Microparticles

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The flow of atmospheric-pressure plasmas over micro-scale particles is a phenomenon of key interest in several applications, such as plasma remediation of toxic gases and materials processing. An example of such a flow is shown in Figure 1. The small scale of the particles in these systems (tenths to hundreds of micrometers) leads to relatively large local Knudsen numbers (~0.01–1.0), meaning kinetic effects are significant in the flow. Resolving these effects numerically requires the use of a kinetic model.

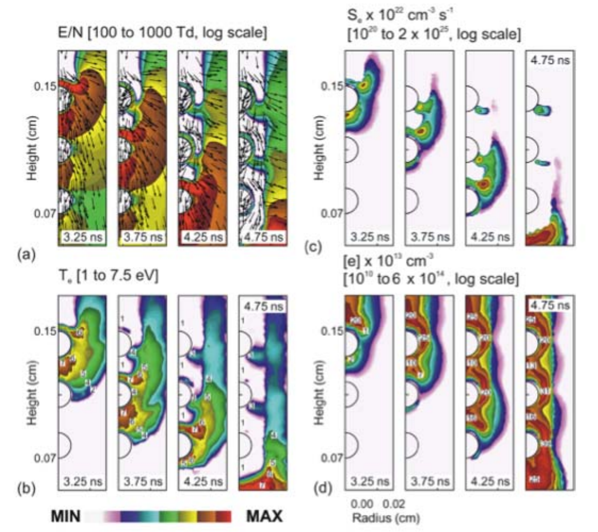


Figure 1: Example of a fully fluid simulation of a plasma streamer interacting with three particles of diameter 80 μm at 1 Atm [6].

We are developing a hybrid fluid-kinetic model to approach the multi-scale problem of high-pressure plasma flow over aerosol microparticles. Similar hybrid models have been successfully developed for neutral gas flows [1–4]. One such model, the Unified Flow Solver (UFS), is capable of utilizing graphics processing units (GPUs) to accelerate its computations by a factor of ~10–100 compared to a single CPU core [5]. This capability is of particular interest for simulating high-pressure plasma flows, as the multi-species, multi-scale nature of such flows results in an extraordinarily high computational cost. Hence, UFS serves as the basis for our hybrid plasma model.

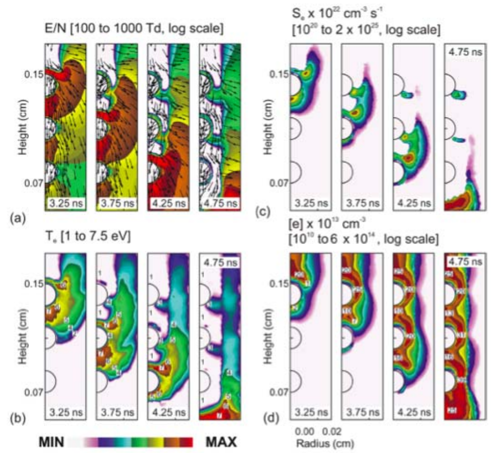
In this work, we are expanding the capabilities of UFS to enable multi-scale simulation of weakly ionized, high-pressure plasmas. We will then develop criteria for when continuum descriptions fail and kinetics methods are required. Finally, we will apply the hybrid model to simulate progressively more complex plasma flows, beginning with flow over a single microparticle. We will also perform a parametric study by varying the number and diameter of the aerosol particles to characterize the effects of localized kinetic phenomena on the flow field.

References

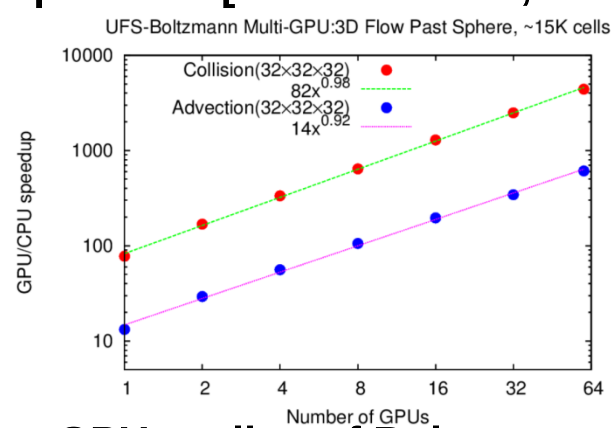
[1] Q. Sun, I.D. Boyd, and G.V. Candler, J. Comput. Phys. **194**, 256 (2004).
[2] T.E. Schwartzentruber, L.C. Scalabrin, and I.D. Boyd, J. Comput. Phys. **225**, 1159 (2007).
[3] V.I. Kolobov, R.R. Arslanbekov, V.V. Aristov, A.A. Frolova, and S.A. Zabelok, J. Comput. Phys. **223**, 589 (2007).
[4] R.R. Arslanbekov, V.I. Kolobov, and A.A. Frolova, AIP Conf. Proc. **1084**, 495 (2008).
[5] S. Zabelok, R. Arslanbekov, and V. Kolobov, J. Comput. Phys. **303**, 455 (2015).
[6] N.Y. Babaeva, A. N. Bhoj, and M. J. Kushner, Plasma Sources Sci. Technol. **15**, 591 (2006).

GPU-ACCELERATED HYBRID MODEL FOR HIGH-PRESSURE PLASMA FLOWS

- **The flow of atmospheric-pressure plasmas over aerosol microparticles (tenths to hundreds of micrometers in diameter) is a multi-species, multi-scale problem that requires resolution of kinetic phenomena.**
- **We are developing a hybrid fluid/kinetic model to simulate these multi-scale flows.**
- **We are expanding the capabilities of an existing hybrid model for neutral gas flows to simulate weakly-ionized plasma flows. This model uses GPU acceleration to reduce computational cost.**
- **We will develop criteria for when kinetic effects dominate the flow field and when the new algorithms are required.**



- **Example plasma flow around particles [Babaeva et al., 2006]**



- **GPU scaling of Boltzmann solver [Zabelok et al., 2015]**