# One Dimensional Model of Atmospheric Low Temperature Plasma Jet

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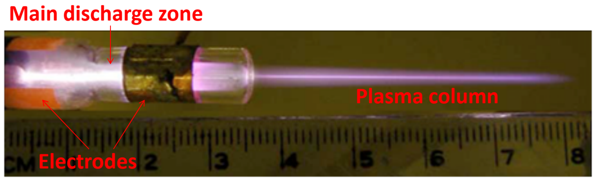



## Introduction

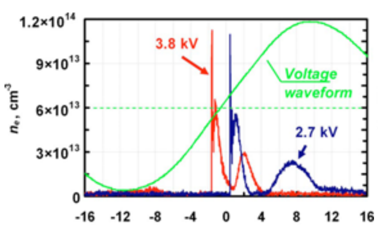
A low temperature atmospheric plasma jet has been developed in our lab to investigate interaction of plasma with living tissue. As indicated in the accompanying poster (Volotskova, ICOPS 2010), cells show strong response to the presence of plasma, leading to an exiting new field of plasma medicine.

In order to better understand this cell/plasma interaction, we need to know the composition of the flow reaching the cell interface. The goal of the work presented here is to determine this composition, and to resolve both radial and temporal distribution of chemical species making up the jet. Although inherently a multi-dimensional problem, in this initial work we model the jet using a 1D radial code.

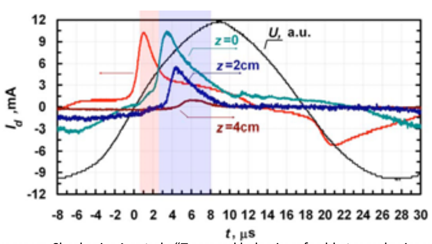
## Low Temperature Atmospheric Jet

Our device uses capacitively coupled discharge to produce a 4cm long plasma column. Helium, the working gas, is ionized between two electrodes in a dielectric cavity. Sinusoidal voltage waveform is applied by the power supply. The jet exits through a 5 mm orifice.

The propagation of the jet in the atmosphere is not completely understood. Our own investigation (Shashurin, 2009) as well as work by many other groups indicate that plasma travels in discrete "bullets" or streamers. Figures below show laboratory measurements of temporal evolution of plasma density in a streamer, as well as the discharge current in the column. The purple shaded region indicates the streamer while the blue region is plasma decaying in the column.



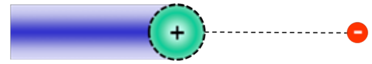

Shashurin, A., et.al., "Temporary-resolved measurement of electron density in small atmospheric plasmas", APL, 96, 171502



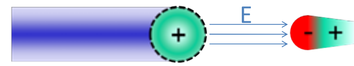

Shashurin, A., et.al., "Temporal behavior of cold atmospheric plasma jet", APL, 94, 231504

## Streamer Propagation Model

We follow the model of Dawson, 1965 to describe the propagation of the column. This model is described schematically below.

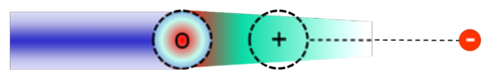


1) The jet consists of a charge neutral plasma column terminating in a positive head contain O(9) ions. A single electron is born ahead of the head by photo-emission. The position where the electron is created corresponds to the distance at which reduced electric field $E/p = 30$ v/cm Torr.




2) The electron starts moving towards the positive head due to self-imposed electric field. Along the way, it gains energy and starts ionizing background gas. The field is given by $E_z = \frac{qN}{4\pi\varepsilon_0 r^2}$, where $N$ is the number of ions in the head.

3) Electron avalanche ensues. Velocity of the electron front can be estimated from $v_d=\mu E$. Time of flight is thus related to axial position by $t=z/v_d$. We apply a radial coordinate system centered on the electron head. Radial density variation is governed by the species continuity equation $\frac{\partial n_i}{\partial t} + \nabla\cdot\Gamma_i = S_i$ where $S_i$ is the species creation rate (reactions from Sakiyama 2007) and $\vec{\Gamma}_i = \pm n_i \mu_i \vec{E} - D_i \nabla n_i$. Electric field is computed from the Poisson eq. Integrating the diffusion equation, we obtain species concentration as a function of axial distance from the streamer head.

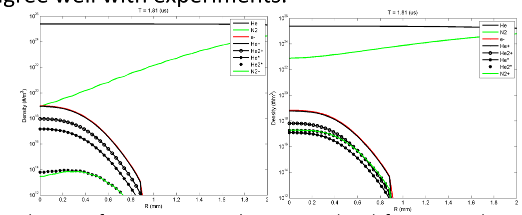


4) Electron front reaches the positive head, neutralizing it. Plasma column is connected to the power supply which provides energy temporarily sustaining the column. Another electron is generated by photo-emission ahead of the new positive region and the entire process repeats. Electron energy is computed from $\frac{\partial n_e \varepsilon}{\partial t} - \frac{5}{3}\nabla\cdot\left[D_e \nabla(n_e\varepsilon) + \mu_e E n_e \varepsilon\right] = Q_{ja} + Q_{jr} + Q_c + Q_{mt}$ where the terms on the RHS correspond to axial and radial joule heating, heat loss (or gain) due to chemical reactions and heat loss due to momentum transfer collisions with background gas. The $Q_{ja}$ term is the primary heating term and is calculated as $Q_{ja}=n_e e v_d E_z$. Once the electrons reach the plasma column, this term is computed from $Q_{ja}=J_x^2/\sigma$, where $J_x$ is the time-varying experimentally measured discharge current density.

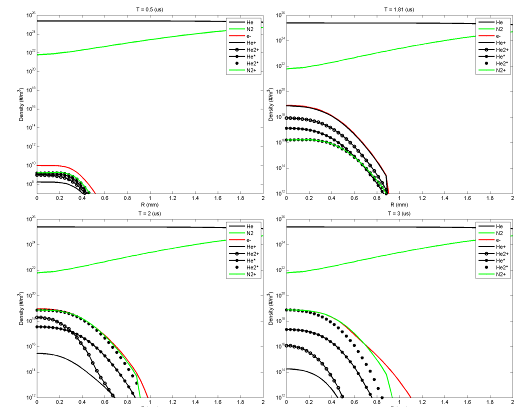
The above model is implemented in Matlab using an implicit scheme. Integration time step is adjusted automatically based on flux and the species creation rates. Simulation commences with electron density corresponding to a single electron distributed over the 0.4mm luminous core region. Densities of background helium and nitrogen gases are computed by solving binary diffusion for 1cm, 2cm and 3cm axial positions, assuming flow velocity of 8 m/s.

## Results

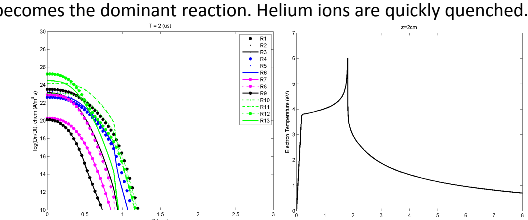
The simulation predicts 1.8μs streamer formation time and O(19) m$^{-3}$ plasma density. Both values agree well with experiments.



Distribution of ion species in the positive head for 1cm and 3cm axial locations. Greater concentration of nitrogen ions is seen at 3cm due to increased diffusion of nitrogen into the beam.



Temporal evolution for the 2cm axial location. Nitrogen ions and excited helium dominate initially, but helium ions become more prevalent as the electron temperature increases. The temperature drops once electrons reach the head and Penning ionization becomes the dominant reaction. Helium ions are quickly quenched.



Chemical reaction rates at 2cm shortly after electrons reach the positive head. R12 corresponds to Penning ionization. Temporal evolution of electron temperature is shown on the right. At 1.8μs, electrons reach the positive head and heating mechanism changes.