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 (Volotkova, 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.

Streamers 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 $E/p = 30 \text{ V/cm Torr}$. Time of flight is thus related to axial position by 

$$ t = \frac{z}{v_d} $$

With $v_d = \mu E$, where $\mu$ is the mobility of the electron.

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 $E = -\frac{qN}{4\pi\varepsilon}$, where $N$ is the number of ions in the head.

3) Electron avalanche ensues. Velocity of the electron front can be estimated from $v_d \propto \sqrt{E}$. Time of flight is thus related to axial position by $t = \frac{z}{v_d}$. We apply a radial coordinate system centered on the electron head. Radial density variation is governed by the species continuity equation: 

$$ \nabla \cdot \nabla \cdot J_S = 0 $$

where $J_S$ is the species creation rate (reactions from Sakiyama 2007) and $Q_{ja} = e N v_d E z$. The 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 new positive region and the entire process repeats. Electron energy is computed from $Q_{ja} = e N v_d E z$, where $Q_{ja}$ is the time-varying experimental 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 0.4 mm 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) m³ plasma density. Both values agree well with experiments.